An *in-vitro* evaluation of resonant frequency analysis to measure fixed bridge stability

By

Khaled A. E. Omer

October, 2011

Thesis submitted in accordance with requirements of University of Liverpool for the degree of Doctor of Philosophy (PhD)

The Faculty of Health and Life Sciences

School of Dentistry

Restorative Dentistry (Fixed Prosthodontics)

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Acknowledgements

I would like to thank my supervisor Professor Callum Youngson, for the great support that, he has given to me over the many years to complete this PhD work. His assistance has had improved the methodology of my work and thesis preparation. He has always given me his time, advice, constructive criticism, proof reading and great effort throughout the period of study for my degree, and for that a massive thank you to him.

I would also like to thank Dr Liam Boyle and Dr Kathryn Fox who supervised my work, for the guidance, proof reading and assistance they have given to me throughout the study and to Dr AJ Preston for all the help.

I am also very grateful for the technical support that I received from Paul Kelleher; for helping in designing, and constructing stone models and metal bridges that were required for *in-vitro* study. His patience and assistance in improving the laboratory method of my work and in achieving a consistent repeatable method *in-vitro,* is very well appreciated. A further mention also to be given to Dr Nigel Bubb for his assistance with Universal Testing Machine (UTM) at Leeds Dental Institute at The University of Leeds and for his advice in preparing the stone casts, using the UTM and in preparing the computer for recording the UTM results. A special thanks to my family for the huge amount of support that I received throughout the period of my study; from my wife Jamela who has shown never ending patience to allow me to complete the study, from three daughters Aia age 18 at University of Salford, Ghada age 15 in Year 11, and Tasneem 16 months; from my two cheeky boys Mohamed age 11 in Year 7 and Mohnad age 9 in Year 5. They have been a wonderful entertainment and provided lots of joy and pleasure during times of stressful working.

A massive thank you to my parents, especially to my great father "Abulgasem" and lovely mum "Fatma" for their tremendous support throughout my academic career life and to whom I dedicate this PhD, and to my brothers and sisters who are always on help when I need them.

Declaration

This thesis is the result of my own work. The material contained in this thesis has not been presented nor is currently being presented, either wholly or in part for any other degree or other qualification.

The research work was carried out in the School of Dentistry, University of Liverpool.

Khaled A. E. Omer

Abstract

Conventional fixed bridge prostheses may fail due to one or more loose retainers, which may be difficult to diagnose. An objective and reproducible investigation to identify, at an early stage, loosening of a retainer could be of significant benefit. The aims of the current series of investigations were to record retrospectively the clinical performance of different types of conventional fixed prostheses used to replace missing teeth and to determine whether Resonance Frequency Analysis (RFA) was capable of measuring bridge stability, *in-vitro*.

One hundred and twenty two patients with 168 bridges were referred to two consultants at the Department of Restorative Dentistry at Liverpool Dental Hospital between Jan 2004 – Dec 2008 with fixed prosthesis problems. Fixed-fixed designs were the most common (77.9%), with cantilever bridges constituting 19.0% of the total. The most frequent cause of failure (39.0%) was associated with a post and core abutment. Apical pathology was found in 20.2%, dental caries in 14.8% and loss of retention in 11.9%. Fixed-fixed bridges were therefore chosen for further study. *In-vitro* pilot studies were subsequently undertaken to determine the feasibility of using resonance frequency analysis (RFA) on all-metal fixed-fixed bridges affixed to different models (wholly dental stone, or incorporating a simulated periodontal ligament) and to determine a reliable method to record this using an Osstell Mentor apparatus. The use of a buccal approach to record RFA values was validated.

Based on the results from the pilot studies and a subsequent power analysis to set sample size, 100 models with standardised acrylic tooth abutment analogues and simulated periodontal ligaments were fabricated. All-metal fixed-fixed bridges were constructed from the first molar to the first premolar using standardised methods on models based with dental stone to mimic 100% (n=50) or 50% (n=50) bone support. In each case, two equal groups of 25 specimens had either both retainers cemented, (control group) or the premolar left uncemented (test group) to mimic clinical failure, cemented by a second operator to allow blind analysis. A magnetic component (Smartpeg) was subsequently cemented to the bridge using low-shrink composite resin and the Osstell Mentor used to measure bridge stability expressed as Bridge Stability Quotients (BSQ). The BSQ recorded at the premolar site in both 100% and 50% bone support models demonstrated a highly statistical significant difference ($P<0.003$) between the control and test groups. ROC analysis determined that a cut-off point was BSQ ≥60 suggesting that the fixed bridge was stable (cemented to both abutments) whereas a BSQ ≤59 indicated a risk of the bridge being uncemented to the premolar. All 100% bone support models were subsequently tested to failure in tension using a Universal Testing Machine with a 500 (N) load cell and cross-head speed of 10mm/min. 37% of specimens from the control group debonded at loads between 82 to 120N with the other 63% failing through extraction of the analogue/fracture of the model. 89.2% of the test group specimens failed by extraction of the tooth analogue from one or both ends at loads below 50N. Statistical analysis using Kruskal Wallis tests demonstrated that the destructive testing could detect a highly statistically significant difference between the test and control group ($P<0.0001$)

These investigations identified mechanical and biological factors associated with failure of conventional fixed bridges and demonstrated that resonance frequency analysis measurements was able to identify, reliably and non-destructively, stable bridges and those with one retainer uncemented, *in-vitro*. With further developments of the technique it may be possible to identify fixed-fixed bridge failure clinically and provide appropriate early clinical intervention.

Table of Contents

3 Figures

4 Tables

1 INTRODUCTION

If a tooth is congenitally missing, fails to erupt, or is lost, the effect may vary greatly depending upon many factors. Factors include: which particular tooth is involved, whether any other tooth/teeth have been lost in the same arch, the teeth articulation and the local and general periodontal condition. In addition, drifting or tilting of adjacent teeth may also take place, and the extent of this depends mainly on the age, and periodontal condition of the patient, the amount of intercuspation and the tooth position in the arch.

Therefore in order to avoid the problems mentioned in the previous paragraph, it is desirable to prevent tooth loss if possible and plan early so, that when required, the teeth can be replaced as soon as possible (Roberts 1980).

Ramfjord (1974) described how missing teeth can be successfully replaced with fixed bridges prostheses in order to improve patient aesthetics, phonetics, comfort, and function and to maintain the health and integrity of the dental arches

There are options of restoring lost teeth; dental implants, removable prostheses, and fixed bridge prostheses. Dental implants and removable prostheses are not the scope of this research. A fixed prosthesis is a prosthetic appliance that is permanently attached to remaining teeth, which replaces one or more missing teeth. It consists of a retainer (placed over the prepared natural tooth), the abutment (natural tooth/teeth), the pontic (an artificial tooth) and the connector (joint or solder).

The survival of any fixed prosthesis depends upon patient satisfaction, the continued integrity of the retainers cemented to the abutment teeth and the health of the supporting tissue. Failure of any one of these can be considered as failure of the bridge. Dental bridges may fail for many various reasons; some of which include loss of retainers (Karlsson 1986), dental caries at the abutment tooth/or teeth (Roberts 1970; Foster 1990) periodontal disease (Nyman and Lindhe 1979) or fracture of bridge units (Hammerle 1994).

Loosening of a retainer in a fixed bridge (may or may not because of luting cement loss) is one of the most common clinical complications of fixed prostheses but may be difficult to determine and to diagnose. Retainer failure is a challenging situation especially when luting cements fail under a fixed retainer while another retainer is still cemented (Verrett and

Mansueto 2003). Karlsson (1986) reported that 12.6 % of patients had undiagnosed loose fixed prostheses retainers.

One significant factor in this most challenging scenario is that bridges are commonly affixed to two teeth, one either side of the space. Failure of the luting cement and/or loss of retention on one of these retainers are disguised by the physical retention offered by the other retainer. The loss of retention, due to failure of the luting cement, allows ingress of bacteria that can rapidly cause caries of the underlying tooth. Lack of salivary flow around the failed retainer, and the absence of dental enamel (removed during preparation for bridge) exacerbate the rate of caries. When failure is eventually noticed by the patient or dentist the failed abutment tooth is often unrestorable.

A method to identify early loss of retention of a fixed bridge would be of a significant benefit. If this could be recognised predictably using a non-invasive method before decay has taken place, there are several advantages that could be gained. These include removal and recementation of the existing fixed bridge. In addition, the early intervention may increase the likelihood of maintaining the retainer with significant biological benefits. Early diagnosis may prevent the need for a longer-span bridge. As longer span fixed bridges fail sooner that smaller bridges, replacement of long spans is often not possible with a fixed bridge and a removable partial denture (with psychological and biological effects) or dental implant treatment option, which is associated with morbidity and financial implications, may be the only alternative.

Although the success or failure of conventional fixed bridges is affected by a number of factors, the present study focuses on detecting the loss of retention of fixed prostheses in vitro, by using a novel application of chair side resonance frequency analysis (Osstell Mentor) in the fixed prosthodontic field.

The overall aim of this thesis is to investigate whether an electromagnetic resonant frequency apparatus (Osstell Mentor, Integration Diagnostics AB, Gamlestadsvägen 3B, SE-415 02 Goteborg, Sweden) is capable of measuring bridge stability, *in-vitro*. Specific research questions which will be addressed in this thesis are:

- Is resonance frequency analysis (RFA) an appropriate method of measuring a bridge stability *in-vitro*?

- Does the use of RFA have the potential to differentiate between uncemented (moving) fixed bridges and cemented (stable) fixed bridges in the laboratory?

The remainder of this thesis is structured as follows:

Chapter 2: provides the background to the history of replacing missing teeth with fixed prostheses. The advantages and disadvantages of replacing missing teeth, performance of different designs of fixed prostheses and various biological and mechanical causative factors that affect fixed prostheses failures are discussed. This chapter also introduces the literature on the development of resonance frequency analysis apparatus, its principle, uses and calibration in clinical measurements of dental implant stability.

In chapter 3, the aims and objectives of the retrospective study are outlined. The assessment of performance of different fixed prostheses designs from case notes reviewed in a retrospective service evaluation is presented. The different factors contributing to fixed prostheses failure are analysed, discussed, compared to other results from the literature and a summary drawn from the analysed data.

Chapter 4 presents the pilot studies conducted to simulate the performance of different fixed prostheses designs on models *in-vitro*. The feasibility of using resonance frequency analysis (RFA) apparatus to measure bridge movement is investigated. The results and discussion of this preliminary work are analysed and recommendations for inclusion into the main experimental study are provided.

In chapter 5, the resonance frequency analysis apparatus (is used on different models *in-vitro* to investigate simulated 100% bone support and 50% bone support. Groups (control and test groups), were allocated using a stratified approach and the values of RFA measurements were recorded from a standardised position of the Osstell probe after standardisation of convergence angles of all preparations to achieve optimum retention of the fixed bridges.

The main findings of this study are statistically analysed, interpreted, and a discussion of the results, including limitations of the studies is presented. Recommendations for further work are discussed.

2 LITERATURE REVIEW

2.1. Introduction

This chapter first reviews the literature to provide a brief description of the history of fixed prostheses, and describes the advantages and disadvantages of replacing. This is followed by a review of literature on clinical performance of different fixed bridge designs. The literature on causes of failures of fixed prostheses with different statistical percentages is also reviewed.

An introduction to resonance frequency analysis (RFA) is given and as this method has been used for assessing the stability of dental implants, the literature on various generations, principles of RFA is reviewed.

2.2. History

Restoring and replacing missing teeth with fixed prostheses has been possible since at least the Seventh Century B.C. by the Phoenicians. They used soft or rolled gold and gold wire soldered for their bridges (Roberts 1980). According to Roberts (1980) who included a review of the history of fixed prostheses in his book, the next known mention of fixed prostheses comes in the second half of the Sixteenth Century. Pierre Fauchard (1678-1761) is considered to be the founder of modern scientific dentistry. He used strips of gold, enamelled and then riveted to bone as artificial teeth. He also removed root canal tissue in order to place pivots made of gold or silver, but their success was not clear. In 1844 Goddard wrote in his textbook that "human teeth are best as artificial teeth with the exception of porcelain". G.V.Black (1836-1916) developed dentistry to new standards and enabled the dentist to use the basic principles more clearly than previously. Chayes, in 1914, identified the significance of normal physiological movement of the teeth within the tissues and thus he advocated the fixed-movable bridge design. He also observed that these bridges had a longer life, although he did not record how many years they lasted (Roberts 1980). According to Roberts (1980), Hildebrand (1937) reported that the result of his longitudinal studies of patients treated with restorative bridgework and he reported only a few successful bridges. In the early dental literature the definitions are often less clear and it is not obvious whether success or survival is considered. In 1955 Morrant reviewed the results of a recall check-up on 74 bridges made at the Eastman Dental Hospital over a 2 year period. He noted that most of the bridges classified as failed were a result of a loss of retention; Failure of unknown reason was noted more with fixed-fixed bridge designs. Bachlund and Akesson (1957) concluded, after 2 years follow up, that the most common factors in the failure of bridges were a high secondary caries rate (in 69 % of the cases) and mobility of the bridge abutment.

Kantorowicz (1968) retrospectively reviewed 172 patients (but the total numbers of bridges was not provided) with bridges constructed by staff and students at the Royal Dental Hospital between 1959 and 1965. He concluded that the overall failure rate recorded was 15 % of all bridges and the average age of the bridges at failure was 3.4 years.

Roberts (1970) conducted a retrospective study of the failure of 2000 retainers in 1,046 bridge prostheses at the Eastman Dental Hospital in between 1952-1964 and concluded that the full crown should be considered as the retainer of choice in fixed prostheses, because of its low failure rate. In this study, the failure rate in anterior retainer teeth was 2.7 % and using posterior full crown as retainer was only 0.5 %. It indicates that the reliability of this form of retainer and its advantage increasing the retention form. The study also showed that post crown restoration is best to be avoided as a major retainer because of their high failure rate which was about 4.35 % per year. He concluded that the causes of failure in his study were poor retainer design, cementation failure, recurrent caries and mechanical failure. Karlsson (1986) examining fixed bridges made by general dental practitioners in a major community in Sweden, reported in a long-term retrospective clinical study 10 years after fixed bridge cementation, that 93% of the bridges cemented were still in function. Failures were due to lose retainers and it was noted that an open margin was often related to dental caries. Many clinical studies have been conducted to evaluate the survival rate, longevity and possible causes of failures for different types of bridges.

There have been many surveys of fixed prosthesis success and failure. The main forms of these are either prospective or retrospective.

The prospective surveys follow restorations from a selection of patients, from placement and through a review period (often of varying lengths). A retrospective survey, however, examines a cross-section of restorations placed, often in different locations such as general or specialist practice; or between dental hospital and general dental practitioners. These surveys are important as they can help to identify the possible causes of failure and the longevity of the restoration following placement as well as possible factors that contribute to a favourable outcome. Jerge and Orlowski (1985), who mentioned that, the disadvantages of the retrospective observations are that they are less reliable when detailed information is necessary, and not every retreatment is recorded, defined the term "prospective". This can led to an inaccuracy in the results.

2.3 Replacement of missing teeth

2.3.1 Advantages of replacing missing teeth

i. Appearance; for many patients with missing anterior teeth , appearance is an important consideration and concern regarding missing teeth has been shown to be the principle reason for more than fifty percent of attendance to a Restorative Consultant service at one dental hospital (Alshammary 2000). Not only are the incisors and canines important as it has been reported that the first and second premolar have an important aesthetic function and if one of these two teeth is missing in a quadrant it will result in negative aesthetic situation which requires prosthetic replacement (Kayser 1981). The importance of the aesthetic function of the upper premolars is in agreement with the findings of Silness (1970), Valderhaug, and Karlsson (1976).

ii. Ability to eat; Many patients manage to eat quite successfully with missing posterior teeth, and the acceptance of this, without prosthetic replacement has been termed the "Shortened Dental Arch". However, the more teeth that are missing, the more important is a replacement to maintain 20 occluding units wherever possible (Kayser 1981). The length of the dental arch in the premolar and molar area was expressed in occlusal units i.e. pairs of occluding posterior teeth. In 1977, Kayser and van der Hoeven investigated the relationship between masticatory capacity and occlusal units through chewing test procedure that based on the release of light absorbing material. Kayser (1981) measured the influence of the shortened dental arch on the remaining dentition and the chewing test showed a highly significant correlation between masticatory capacity and number of occlusal units. This result is in agreement with the work of Helkimo *et al.*, (1977) where different methods were used.

ii. Occlusal stability; although occlusal stability may be lost initially when teeth are extracted, in some patient this is not true in the longer term (Craddock and Youngson 2004). Occlusal harmony means the absence of occlusal interference, which allows smooth comprehensive movements of the mandible in all excursions with the teeth together without discomfort. The eruptive tooth movement process continues during the life of the tooth, where the tooth moves from its developmental position within the jaw, to appear in the oral cavity in the axial direction (Craddock and Youngson 2004).

iii. Speech; The upper incisors teeth are the most important in speech, and when they are missing they require replacement to improve articulation.

iv. Periodontal splinting; Periodontal disease gradually destroys the supporting tissues of the teeth and, in advanced stages if not treated, the breakdown of the periodontium may progress to a level where extraction of one or several teeth is needed. In this circumstance, prosthetic rehabilitation is often needed to restore such missing teeth in order to achieve and restore function and /or aesthetics. Nyman and Lindhe (1979) demonstrated that on a reduced remaining periodontium where it is less capable of withstanding normal masticatory forces during chewing, the related tooth/teeth may be displaced, exhibit mobility or extraction. They stated that provide fixed bridge prostheses as a periodontal treatment for such dentition and at the same time often they act as a cross-arch splinting effect.

v. A feeling of completeness; within some cultures it is not acceptable to have teeth missing. Those patients gain considerable psychological benefit from a fixed bridge replacement of their teeth rather than wearing removable partial dentures.

vi. Wind instrument players; Missing anterior teeth can have a disastrous effect on the embouchure and thus affect the quality of sound produced by some players of brass or reed instruments.

2.3.2 Disadvantages of replacing missing teeth

i. Damage to tooth and pulp; whenever a tooth is prepared, there is a danger to the pulp. This is greater for crown preparations (Valderhaug *et al.,* 1997, Saunders and Saunders 1998) and even more threat to the pulp when teeth are prepared for bridges (Cheung *et al.,* 2005). However, these studies were all cross-sectional rather than prospective and so aspects such as pre-crown restoration status, apical status, preparation, and temporisation are all "uncontrolled" and this can make it difficult for definite conclusions to be drawn.

ii. Secondary caries; the presence of a restoration margin can accumulate plaque; any marginal cement dissolution at the margin of a bridge could carry the risk of micro-leakage and lead to caries of the natural tooth (Roberts 1970, Karlsson 1986).

iii. Failures; the chances of failures are present and possible for any prosthesis. The failures may be technical (loos of retention, cement loss, abutment fracture, and post fracture) or biological failures (dental caries, endodontic problem).

iv. Financial and biological cost of the procedure (see i) and discomfort (morbidity) during the procedure.

2.4 Bridge Design

There are four basic designs of bridges (Smith and Howe 2007);

i. Fixed-fixed bridge;

This has a rigid connector at both ends of the pontic. The pontic is located between two or more abutments at both ends. The abutment teeth are therefore rigidly splinted together. The retainer is that part of the bridge that made of artificial materials and been cemented over the prepared abutment teeth. It can be conventional fixed-fixed bridges (CFFB) where there are abutment teeth prepared or reduction on both side of the missing place and coverage retainers (full or partial) cemented by permanent cement. The other type of fixed-fixed bridge (RBFFB) is resin bonded fixed bridge in which both ends of the fixed bridge having metal wings on the lingual or palatal surface of the abutments and cemented directly to the tooth surface by resin composite material.

ii. Fixed-moveable bridge (also known as fixed-supported);

It has a rigid connector, usually at the distal end of the pontic and a movable connector that allows some vertical movement of the mesial abutment tooth (the minor retainer)

iii. Cantilever bridge (occasionally described as fixed-free)

It provides support for pontic at one end only. The pontic is attached to a single retainer or more retainers splinted together, but it has no connection at the other end of the pontic. The abutment tooth/teeth for short span bridges are usually distal to the span. It can be conventional cantilever fixed bridge (CCFB) or resin bonded cantilever fixed bridge (RBCCB).

iv. Spring cantilever bridge

Spring cantilever bridges have been restricted to the replacement of upper incisor teeth when the teeth either side of the gap were sound. Only one pontic can be attached to the end of a long metal bar placed onto the palate connected to a rigid connector on the palatal side of a retainer(s). Spring cantilever bridges are no longer in common use and minimum preparation bridges have replaced them.

2.4.1 Minimum preparation bridges (Resin Bonded Bridges, Rochette or Maryland bridges)

2.4.1.1 History of resin-bonded bridges

Resin-bonded bridges (RBBs) were first developed from a periodontal splint (Rochette, 1973) and became recognised as a conservative restoration for replacing missing teeth. In certain situations RBBs can be considered as an alternative to conventional fixed-fixed bridges and they can be used in tooth replacement, orthodontic and periodontal therapy (Zalkind *et al.*, 2003).

Rochette was the first to adopt the resin-bonding technique, to attach a fixed periodontal splint to enamel without removing tooth structure. He described the use of a perforated gold casting framework for splinting periodontally involved lower incisors (Rochette 1973).

Isben (1973) described the direct resin bond between extracted natural teeth or an acrylic tooth to an abutment tooth (or teeth). Several years later Simonsen (1978) outlined another method, using composite pontics attached to adjacent teeth. Despite moderate success of some of these techniques, failure tends to occur through fracture of composite connectors at the pontic/abutment tooth interface.

Howe and Denehy (1977) reported the first use of the Rochette splint to replace missing teeth. They used this technique for anterior fixed bridge and Livaditis (1980) described using it for posterior replacement.

2.4.1.2 Means of retention of RBBs

In order to enhance the resin-to-metal bond, a variety of metal treatments was developed. These included:

i. Macro-mechanical retention;

This technique used a mesh inside a solid retainer (wing) to give mechanical retention (Taleghani and Morgan 1987). Further techniques included the use of: acrylic beads incorporated on the fitting surface of the retainer wings, and then duplicated in the casting to produce the required retention (LaBarre and Ward 1984). The retentive systems using these techniques were, however led to poor fit at the margins of the restoration causing frequent de-bonding.

ii. Micro-mechanical retention methods were developed, using electrochemical and chemical methods (Livaditis 1982, 1986). The electrochemical etching was developed at the University of Maryland, which provides the term "Maryland Bridge".

Electrochemical etching is technique sensitive and some precaution is needed for better results. Over-etching produces an electro polished surface; any contamination of the etched surface may reduces bond strength (Wiltshire 1987)

The difficulty in etching procedures which included the fact that it can only be used on certain alloys and the concerns about handling and properly disposing of the dangerous chemicals, led to the development of other methods such as a sandblasting technique. In this technique, alumina (aluminium oxide) particles (between 50 and 250μm) are blasted under air pressure to produce a roughened layer over the metal surface. Where base metals are used this surface will then oxidise. Sandblasting is less technique sensitive than etching, less costly and the abraded surface is relatively easy to re-sandblast if it is become contaminated during try-in of the casting (Bassi 2002).

Another methods of improving micro-mechanical retention are using of Tin plating and Silicoating. This will increase the surface area for micromechanical retention.

2.4.1.3 Advantages and disadvantages of RBBs

The main advantages of RBBs after Bassi (2002)

i. Minimal tooth preparation compared with conventional bridges - hence the pulp not at risk (reduced operative morbidity).

ii. Restoration margins can usually be kept supra-gingivally to maintain gingival health.

iii. Chair side times and laboratory cost can be reduced.

iv. Reversible technique.

v. No need for anaesthesia.

vi. Relatively easy to prepare (depending on amount of preparation).

vii. Often no need for a temporary restoration.

The technique has several advantages over conventional bridgework, especially in relation to conservation of tooth structure and reversibility. However, variation in technique, patient selection and clinician experience are known to affect success (Creugers 1991). It should be noted that these latter variables also affect the survival of conventional bridgework.

The main disadvantages (Bassi 2002);

i. A higher failure rate than conventional bridges.

ii. It benefits from a large surface area of enamel tooth surface.

iii. With less tooth preparation, occlusal interferences are possible that can be eliminated only after bridge cementation.

iv. No assessment of function at try in.

v. Technique sensitive

vi. A Risk of metal display and aesthetic problems if metal "shine through" the abutment teeth.

vii. Limited indications.

2.4.1.4 Indications and Contraindications of RBBs

Resin-bonded bridges tend to be indicated in the following circumstances; a single missing incisor tooth (caries-free or with only minimal restorations present) with a favourable occlusion.

Contraindications; an unfavourable occlusion, abutment teeth with large carious lesions, extensive restorations or severe tooth wear, patient with known hypersensitivity to non-precious metal, more than one pontic.

2.4.1.5 Bridge design of RBBs

There are three common designs based on the retainer type and connectors; fixed-fixed RBBs, Cantilever RBBs, and hybrid RBBs. A cantilever RBB is usually limited to the replacement of one tooth, and this is most commonly the lateral incisor. With the fixed-fixed bridges, one or more retainers are placed on either side of the pontic. Hybrid bridges consist of both resin-retained and conventional (crown) retainers within one bridge framework.

The "survival rate" of RBBs can be defined as the RBB remaining in situ with or without modification for the observation period. The "success rate" was defined as the RBB being free of all complications over the observation period (Pjetursson and Lang 2008).

The independent free-standing nature of the single cantilever bridge allows movement to occur without stressing the cement lute. The advantages of two unit cantilever RBBs, it is more conservative to tooth tissue than its fixed-fixed bridges (Botelho 2000). It is easier, quicker to prepare, easy to record an impression, and simpler to cement. Also, these factors along with lower laboratory costs it makes this type of treatment option is affordable for patients (Botelho 2000).

2.4.1.6 Factors affecting the survival of RBBs

Careful case selection and treatment planning, ability in performing the clinical work required, proper material selection to improve survival rates of bridges have been highlighted (Pjetursson *et al.,* 2008). Choice of abutments with adequate crown length, a large surface area for wraparound (the framework design should extend around 180 degree of the axial tooth surface), favourable occlusion, are indicative factors for RBB success (Botelho *et al.*, 2000). However, they mentioned that, short clinical crown, limited inter-occlusal distance; edge to edge occlusions are considered to be the contraindications for RBBs.

In order to improve the survival rate of RBBs there are a few factors to be considered. The early use of acid etched resin-bonded prosthesis was accomplished with no preparation of the abutment of the teeth (Rochette 1973; Howe and Denehy 1977). However, definite tooth preparation for permanent bridges has been recommended (Simon *et al.*, 1992; Barrack and Bretz 1993). In addition, the importance of effective moisture control during bridge placement and the use of rubber dam has been stressed (Chang *et al.*, 1991; Morgan *et al.*, 2001). It has also been highlighted that occlusal factors and control of parafunction may be of importance in the success of RBBs (Creugers *et al.*, 1989; Morgan *et al.*, 2001).

It has been shown that there are statistically significant lower failure rates of maxillary RBBs compared to mandibular RBBs (Olin *et al.*, 1991; Creugers *et al.*, 1997). This finding was supported by an investigation conducted by Zalkind *et al.*, (2003) which demonstrated that mandibular RBBs were considerably less successful than those in the maxilla.

Hussey and Linden (1996) concluded that the cantilevered resin-bonded bridges performed well with a low incidence of de-bonding. They concluded that replacements of maxillary lateral incisor, maxillary premolars, and mandibular teeth were more successful than the replacement of maxillary central incisors and canines.

Clinical studies have reported that anterior RBB performance is much higher than posterior RBBs (Boyer 1993; Briggs *et al.*, 1996). This is in agreement with the studies that reported that posterior RBB were associated with a higher failure rate than in upper RBBs (Creugers *et al.*, 1991). He reported that a 75 % survival rate for anterior RBBs at 7.5 years and 44 % for posterior RBBs.

2.4.1.7 Tooth preparation and framework design for RBBs

The early use of acid etched resin-boned prosthesis was accomplished with no preparation of the abutment teeth (Rochette, 1973; Howe and Denehy 1977). Authors suggested that little or no preparation of abutment teeth for this type of prosthesis ensured its reversibility. It has also been stated that the preparation must be extended as far as possible to provide maximum bonding area for the composite resin and it should encircle at least 180 degree of the tooth (called wraparound) in order to increase the resistance of the retainer (Barrack 1984).

The clinical success of RBBs has been attributed to both tooth preparation and prosthesis design (Botelho *et al.,* 2006). Various aspects of tooth preparation have been proposed for successful RBBs; the use of grooves (Crispin 1991, Simon *et al.,* 1992), and rest seats with resistance form (Simon *et al.,* 1992; Rammelsberg *et al.,* 1993) appear to be of important value for clinical retention of RBBs. In addition, the extensions of metal framework, wraparound in posterior teeth are to be considered important in clinical longevity of RBBs (Botelho *et al.,* 2006).

The framework of the bridge should be rigid and have optimal resistance form while allowing good oral hygiene. Resin-bonded bridge retainers are basically partial veneer restorations with little occlusal coverage and clinicians have suggested that the optimal thickness for resin-bonded bridge frameworks should be between 0.3-0.6 mm, depending on the site, stress on the bridge, and the metal being used (Botelho 1999). Retainers should be of sufficient thickness with-out interfering with the occlusion and should have margins and contours that are compatible with periodontal health.

Another important factor of prosthesis design and success relates to the number of units in the RBB framework. Many authors recommend that only a single missing tooth (one pontic) should be replaced (Gratton 1983; Marinello and Belser, 1985) as 3 unit bridges have a much lower percentage of failures than bridges with more than 3 units and the main reasons for de-bonding of RBBs included occlusal stresses, resin cement failure and non-retentive bridge designs (Berekally and Smales 1993).

In general, clinical success depends on case selection, adequate tooth preparation, proper prostheses design, operator knowledge and skill, control of the oral environment. With advancements in both alloy-resin bonding and resin cements, the long-term longevity of bridges can be better predicted and de-bonding of RBBs will be less of a problem.

2.4.2 Conventional fixed-fixed bridges (CFFB)

2.4.2.1 Advantages of CFFB

A fixed-fixed bridge has a rigid connector at each end of the pontic. The abutment teeth are rigidly splinted together; the abutment preparation must be parallel to each other to provide maximum retention and to reduce dislodging forces applied to the fixed bridge.

The advantages of fixed-fixed bridge designs can be recorded (Smith and Howe 2007) as;

i. They provide maximal retention as they have a large surface area.

ii. They are relatively simple to construct as they have a single casting framework.

iii. The design is often the most practical for long span bridges.

iv. The abutment teeth are splinted together in the case of uncomfortable mobility following periodontal bone loss.

2.4.2.2 Disadvantages of CFFB

In contrast to the above advantages the main disadvantages:

i. They may endanger the pulp during tooth reduction that is required to obtain a common path of insertion (Cheung *et al.,* 2005).

ii. They may be difficult to prepare due to multiple, paralleled, retainers required

2.4.2.3 Complications of CFFB

Despite great emphasis being placed on oral hygiene, healthy periodontal tissues, proper case selection and a well performed treatment plan prior to the bridge construction procedures (Hochman *et al.,* 2003), complications do occur.

The complicating biological and technical factors play important roles in the success or failure of bridges and directly affect their overall survival rate.

Biological complications are dental caries, loss of pulp vitality, periodontal disease (Pjetursson and Lang 2008). All these biological processes have some effect upon the supporting tissues.

Technical complications are loss of retention, abutment tooth fracture, fracture or deformations of the frame-work or the laminating porcelain (Pjetursson and Lang 2008). A review conducted by Pjetursson and Lang (2008) showed the result of an estimated 5 and 10 year study of the survival proportion of different bridges designs. They found a 5 year survival of conventional fixed bridges of 93.8 %, cantilever bridges 91.4 %, and resin-bonded bridges 87.7 %. Moreover, after 10 years of function the estimated survival rate decreased to 89.2 % for conventional fixed bridges, to 80.3 % for cantilever bridges, and to 65 % for resin-bonded bridges.

In the study of Cheung *et al.,* (1990) the three major causes of failures were analysed according to the location of the bridge work. Endodontic failure most affected upper anterior bridges. Loss of retention occurred mainly on upper anterior and lower posterior segments. Post-operative pain and sensitivity caused more failure in posterior rather than anterior bridgework.

The trauma of tooth preparation for fixed bridge procedures, the possibility of a pre-existing pulp condition before the procedure, bacterial or chemical irritation caused by cementing agents, marginal leakage, or maybe occlusal trauma post cementation procedure, are possible factors that could affect the pulp leading to possible endodontic problems (Cheung *et al* ., 1990; Fearon & Youngson 2001). Although trauma associated with the tooth preparation was considered the principal reason for pulp death by Karlsson (1986).

Cheung *et al.,* (1990) explained why anterior teeth are more likely to have pulp involvement: Their large pulp size and the amount of tooth reduction required to accommodate the bridge sub- and super-structure. As a result of these factors 70 % of the failures of endodontic origin were in anterior teeth where the teeth are relatively small. However, in other earlier studies, it was concluded that caries was the single most common cause for fixed bridgework failure (Kantorowicz, 1968; Schwartz *et al.,* 1970; Walton *et al.,* 1986). This finding is in agreement with Hochman *et al.,* (2003) report, where they suggested that it was necessary to identify high caries risk patients and promptly induce caries preventive measures such as special diet. However, these studies did not focus upon pulpal effects of bridgework but that caries may also eventually lead to endodontic problems.

The incidence of post-cementation pain and sensitivity in the abutment teeth was higher in posterior that in anterior bridges. Cheung *et al.*, (1990) observed that four out of five bridges, removed due to post-cementation pain were luted with glass inomer cement. Although histopathological studies revealed that glass inomer cement does not evoke any greater pulpal response than zinc phosphate or poly-carboxylate (Heyse *et al.*, 1987), irritation due to the cementing medium might also play a role in the post-cementation pain. One study discussed that this might be explained by the amount of occlusal loading on the posterior teeth and the possible introduction of occlusal interferences although these authors did not examine this hypothesis (Cheung *et al.*, 1990)

As stated earlier, failure may be attributed to several causes; some studies have attributed these to biological and mechanical failures including dental caries and loss of retention and marginal defects (Swartz *et al.*, 1996). Some difficulties in comparing failure rates between studies arise from the fact that the definition of failure used may be highly variable and some authors define a failure only when the entire fixed prosthesis is no longer in situ or requires immediate replacement (Leempoel *et al.*, 1995; Karlsson 1989). The rate of bridge failure also appears to vary according to the circumstances of the bridge placement with some authors attributing over 50% of failure to the dentists and materials used (Maryniuk and Kaplan 1986). This is in agreement with the observation that the longevity and complication rate of fixed bridges will be influenced by the level of skills and academic knowledge of the clinician (Tan *et al.*, 2004). Patients treated in institutions may differ from those from private practice as they may present with higher oral hygiene standards and may be part of a strict maintenance care program (Nyman and Ericsson 1982).

2.4.3 Cantilever conventional fixed bridges

2.4.3.1 Introduction

Cantilever fixed bridges have been defined (Pjetursson *et al.*, 2004) as retainers holding one or more unsupported free-end extension. A cantilever bridge provides support for the pontic at one end only. The pontic may be attached to a single retainer or to two or more retainers splinted together. The abutment tooth or teeth for a cantilever bridge may be either mesial or distal to the span but mostly they are distal. It has been shown (Chai *et al.*, 2005), that it is considered a more favourable treatment option for tooth replacement in combination with fixed prostheses, and it was noticed by some authors that the cantilevered fixed bridgework provided better function in comparison to removable partial dentures, was associated with better oral hygiene and less dental caries, and require less maintenance (Chai *et al.*, 2005).

The options for restoring edentulous spaces are a removable partial denture (RPD), the use of a cantilevered fixed bridge or the placement of dental implants.

2.4.3.2 Advantages and disadvantages of cantilever fixed bridges

The advantages of a cantilevered fixed bridge include; better retention, are associated with better oral hygiene and less caries, and require less maintenance when compared to the removable partial denture. A cantilever bridge design is also more conservative of tooth structure, simpler to prepare and fabricate, and reduce the cost to the patient (Chai *et al.*, 2005).

2.4.3.3 Complications of cantilever fixed bridges

These bridges are indicated ideally where a single tooth is missing, there is a low expected occlusal load and where it can fulfil an aesthetic demand. Despite the facts that cantilever fixed bridges can be successful, failures do occur. Within some studies (Leempoel *et al.*, 1995; *Chai et al.*, 2005) cantilever conventional fixed bridges have been demonstrated to perform as well as fixed conventional bridges. However, other investigations have revealed that cantilevered fixed bridges fail at a higher rate than fixed-fixed bridges (Karlsson 1986 and 1989; Walton *et al.*, 1986). Walton *et al.*, (1986) reported that there was no clear cut relationship between the life span and number of units in a fixed prosthesis. They concluded that the six unit canine-canine fixed bridge had largest life span of average 10.4 years before failure. However, the two unit cantilever fixed bridge had the shortest life span of average of 3.7 years. The possible explanation they gave in their study was that the small sample size (number) of canine-canine prosthesis. Another possible influence is that a private general practitioner performed the restorative treatment in the study conducted by Karlsson (1986) where the pre-operative dental pulp status was unknown and the dentists "thought" the abutment to be vital at time of cementation.

A meta-analysis study (Pjetursson *et al.*, 2007) resulted in an estimated survival rate of cantilever fixed bridges of 81.8% after a 10-year observation period but biological and technical complications were frequent. This is in agreement with an earlier long-term retrospective study conducted by Laurell *et al.,* (1991). In this study all subjects were referred for treatment of periodontal disease and fixed bridgework include two or more unilateral or bilateral cantilever units. They showed that after 10 years 82 % of the prostheses were still in function. They did however mention that special requirements were set up for the design of cantilever prosthesis.

Technical complications such as loss of retention, fractures of abutment teeth and the framework, or veneering porcelain, were reported to be the most common causes of failure that increased with an increasing number of cantilever units and years in service (Karlsson 1989). In a retrospective study by Laurell *et al.,* (1989) found that the high rate of failure in cantilever fixed bridges attributed to loss of retention often in distal retainer crowns. Dahl *et al.,* (1987) (40 %) and Karlsson (1989) (36 %) were reported the highest rate of loss of retention of cantilever fixed bridges.

In a retrospective study of 83 extensive fixed bridges with cantilever units made by general practitioner, Randow *et al.,* (1986) reported an average technical failure rate of 37% after 5 to 7 years, the failures increasing with time in function and number of cantilever units.

Several studies conclude that cantilever conventional bridges perform well with a low incidence of failure. However, not all studies confirm this and so further investigations are required to identify factors that affect their longevity and clinical success.

2.5 Causes of conventional fixed bridge failure

2.5.1 Introduction

Failure can be due to progressive dental caries, periodontal disease, loss of retention, fracture of an aesthetic porcelain facing, connector fracture or an occlusal problem (Cheung *et al.,* 1990). Non-ceramic composite/acrylic bridges may also fail aesthetically due to loss of surface finish associated with wear. In addition, Palmqvist and Soderfeldt (1994) mentioned number of factors that affecting the survival rate of bridges have been analysed in many clinical studies, such as bridge design, the number of teeth being replaced, the periodontal condition of the abutment teeth, the vitality of abutment teeth, the patient's motivation, age and gender, and general health conditions that may affect the survival rate.

Some surveys demonstrate a survival rate of bridges for the first 10 years with more than 90% of the bridges still in function (Karlsson 1986). This survival rate declines, with 60-70% of bridges still in place after 15 years (Valderhaug 1991). The explanation of this decrease in survival rate after 10 years was not exactly known. However, fatigue and ageing of materials could play a role (Creugers *et al.,* 1994). Non-vital abutments also tend to decrease the survival rate after 10 years (Leempoel *et al.,* 1995).

In fixed prosthodontics, there is growing interest in the quality and expected longevity of these relatively expensive treatment options amongst patients and dental professionals. In order to achieve better quality and long-term survival, attention is increasingly being focussed upon the importance of preventive dentistry and periodontal health. Both of these are recognised as having an increased influence on fixed bridge success.

2.5.2 Biological failure

The failures due to biological factors has a direct impact on the survival and longevity of conventional fixed bridges include failures due to extensive dental caries and failures in conjunction with endodontic problems and peri-apical lesion could be developed as a result.

2.5.2.1 Dental caries

The earlier study by Bachlund and Akesson (1957) reported in a two year follow up of crowns and bridges that, a higher secondary caries rate at the margin of the three-quarter crowns when they compare to the full crowns, without mention the reasons.

Secondary caries (along with apical pathology) has been noted to be the most frequent cause of bridge failure (Foster 1990). Loss of pulp vitality leading to root canal treatment is often the result of caries and previous heavy restorations. This is in agreement with Roberts (1970).

A survey published by Akatyev (1979) recording the reasons for removal of crowns and fixed prostheses at one clinic during a 6-month period, concluded that the greatest percentage of crowns (25.2 %) were removed because of caries and its complications. He mentioned that the other causes of failure were fractured solder joints, uncemented crowns, worn occlusal surfaces, and periodontal diseases. He further concluded that about 64% of the patients had caries on the abutment tooth under the loose retainer. Goodacre *et al.*, (2003) reported a similar result, stating that the most common problem following fixed prosthesis construction was caries (found in 18% of cases).

2.5.2.2 Failure of conventional bridges due to endodontic problems

Full metal-ceramic crowns (CMCs) are often used as retainers for fixed prostheses, because of their very strong, retentive property that satisfactorily fulfil an aesthetic requirement. These bridge abutments might have had dental caries, periodontal disease or trauma before having metal-ceramic crowns (Ericson *et al.,* 1966). A Survey by Cheung *et al.,* (1990) reported that about 57% of fixed bridges were due to loss of pulp vitality or presence of a periapical radiolucent area at one or both abutments. They also reported that the survival rates for pulp vitality were estimated to be 84.4% for metal-ceramic crowns (CMCs) in comparison to 70% in case of bridge retainer (BR) after 10 years. The high rate of pulpal necrosis in bridge abutments might be related to the more tooth reduction to prepare one path of insertion. The deeper tooth reduction often results in more traumas to the pulp tissue and increase chances of pulp inflammation (Kim and Trowbridge 1998).

The abutment teeth that are subsequently used in a fixed prosthesis can also subsequently develop pulpal complications as a result of dental caries or preparation, and/or periodontal disease (Selby 1994). These complications are examples of the biological failure of fixed prostheses. As with all tooth preparation, it is essential that preparation should be carried out with copious water-cooling, sharp burs and gentle pressure to limit potential damage to the pulp (Smith and Howe 2007).

The health of the dental pulp may become compromised if there are heavy fillings, or if the unprotected prepared tooth is left with no provisional crown for an extended period. The type of material used to construct the temporary coverage, and the type of cements may also affect the prognosis of the tooth (Fearon and Youngson 2001).

The longevity and reasons for failure in fixed prostheses have been reported in many studies over many years. Some of these gave an indication that pulp necrosis can be detected after fixed prosthesis construction. Bergenholtz and Nyman (1984) concluded that pulpal necrosis can be found in 15% of abutment teeth when compared to non abutments over an observation period of 8.7 years. One retrospective review of the dental literature was revealed that 3% to 25% of the vital teeth that were prepared for complete coverage developed pulp necrosis (Lockard 2002). He conducted a review of the dental literature (1970-1997) which revealed that the wide range of percentages of pulp necrosis could be because of differences in study methodology and design. A significant lower rate of pulpal necrosis is probably due to the cumulative effect of each procedure being completed in sequence without injury to the pulp, not to any single technique.

Many authors consider frictional heat as a major factor in pulp necrosis, however, there are several other essential factors that may contribute to pulp necrosis which include; tooth desiccation, pressure applied during tooth reduction, chemical injury, bacterial infection, cementation and occlusion (Lockard 2002).

Langeland and Langeland (1965) demonstrated that crown preparations made with the use of an adequate air-water spray, showed no pulp reaction. If the air-water spray was insufficient, the dentine burned, and odontoblasts and erythrocytes appeared in the pulpal ends of the cut dentinal tubules. This is in agreement with Seltzer and Benders (1959) study, in which they determined that pulp irritation, was reduced at higher speed, provided that abundant quantities of water were used during preparation.

The diagnosis of pulp necrosis or a peri-apical lesion is not always an easy task; it is based on the patient's complaint, the clinical signs and symptoms, and radiographic findings. However, pulp necrosis can develop but remain undetected because of a lack of radiographic changes and no clinical signs or symptoms which could show that the dental pulp is compromised (Valderhaug *et al.*, 1997). This process can take some time before lesions become detectable radiographically and they might remain undiagnosed until the next examination or until signs and symptoms of infection become obvious.

Mechanical failures such as loss of retention, fracture of porcelain, fracture of the metal framework or fracture of an abutment tooth can also have an effect on the health of the dental pulp (Cheung *et al.*, 2005). The pulp could become non-vital due to mechanical and chemical insults which may be due to; tooth preparation, impression procedure, and absence of provisional restoration and the effect of the temporary or permanent luting cement used.

However, all this is reversible and usually resolves after some time if there is no bacterial contamination (Olgart and Bergenholtz 2003).

The literature demonstrates that at each step in the provision of a fixed prosthesis is it possible to involve an insult the pulp tissue (Brannstrom and Noredenvall 1977; Bergenholtz *et al.,* 1982). One retrospective study has demonstrated, after 10 years that 57% of all failures of fixed prostheses were due to endodontic involvement at one or both abutments (Cheung *et al.,* 1990). Valderhaug *et al.,* (1997) have retrospectively investigated endodontic complications in teeth with an initial vital pulp, and they reported a survival rate of the pulp were 98% after five years, 92 % after 10 years, 87 % after 20 years and 83% after 25 years.

There are many factors that could lead to insult pulp vitality during full coverage construction but a significant factor is tooth position where, in a retrospective study it has been reported that, the anterior teeth were much more affected and associated with a non-vital pulp (Cheung *et al.,* 2005). They reported that over 70 % of pulpal necrosis developed in the maxillary anterior teeth; this was probably due to the large amount of tooth reduction performed for porcelain fused to metal fixed bridge and the relatively large pulp size of anterior teeth. They reported that survival of the vital pulp in teeth restored with a single-unit metal ceramic crown was significantly higher than those serving as an abutment of a fixed-fixed bridge.

The higher incidences of pulp necrosis in bridge abutments (rather than metal-ceramic crowns) might be related to the large amount of tooth reduction to obtain one path of parallelism; this in turn could produce more traumas to the abutment and endanger the pulp tissue (Cheung *et al.,* 1990).

The extensive tooth reduction and deeper tooth preparation could result in more chances of an inflammatory pulp response (Kim and Trowbridge 1998). However, the rate of pulp tissue involvement in study conducted by Jackson *et al.* (1992) showed that proper techniques used during tooth preparation and the process of bridge construction could cause little or no injury to the pulpal tissue. In this context, early work by Stanley and Swerdlow (1959) concluded that the use of combination of high speed, controlled low temperature, and light pressure could result in minimal pulpal irritation.

In order to prevent endodontic complications the following steps might help; careful tooth status assessment, consider conservative treatment options and use of adhesive bridge where possible, avoid over reduction, avoid over-heating, use of a cooling system during preparation, proper provisional protection, proper impression technique, and careful selection of sealing for final restoration against bacterial invasion. All the above appear to be factors in maintaining healthy pulp tissue.

2.5.3 Mechanical failure

Technical failures could contribute to decrease the longevity of the conventional fixed bridges. These include loss or fracture of luting cement with or without loss of retention of between retainers and abutment teeth, fracture of the post and core, fracture of the porcelain veneer, fracture of abutment teeth.

2.5.3.1 Loose retainer and cementation failure

Complete loss of retention is not a common cause of failure of individual crowns, however, because of the more complex dislodgment forces acting on fixed bridges, one of most frequent failure patterns is one retainer becoming loose but the other remaining attached to another abutment tooth (Smith and Howe 2007). When one retainer of a fixed-fixed bridge becomes loose, a problem quickly develops. The open margin of the loose retainer allows increased dissolution of the luting cement (which may have failed mechanically as the adhesion/cohesion of the lute fails). Without cement, plaque can formed on the exposed tooth surface. This is often exacerbated by the lack of salivary flow around the leaking preparation and so the buffering and remineralising properties of saliva are lost and secondary caries develops quickly.

The main problem in loss of retention of any retainer is that it may remain unnoticed for a long period and dental caries can develop as a result. One investigation has reported that 41% of patients were not aware they had a loose retainer until informed by a dentist (Curtis *et al.,* 2006). When patients are aware, of a failure it is usually because they are aware of increased movement developing in the bridge or they start to experience a bad taste from under the loose retainer.

To check retainer movement, a little pressure on the loose retainer often causes salivary bubbles at the retainer margin and this is often regarded as proof that the retainer is loose. If this occurs in the case of fixed-fixed resin bonded bridges (FFRBBs), one solution is to section the loose retainer, leaving the bridge as a cantilever RBB. Another option that has been advised (Smith and Howe 2007) is that the first stage in investigation of a de-bond retainer is to remove the resin bridge from the attached retainer; clean it, sandblast it, and re-cement the bridge.

In contrast, if a cantilever bridge (conventional or RBB) loses its retention the same is true if both ends of a fixed-fixed bridge become loose); it results in the bridge falling out. In this case the damage is usually less and there is little or no chance of plaque retention with subsequent caries and, usually, the patient will contact his dentist.

One of the frequent fixed prosthetic complications that have been reported is that of a loose retainer (Goodacre *et al.*, 2003). However, this may go undetected in a CFFB design as the bridge is held in place by the other retainer. The loosening of a bridge retainer occurs with a frequency between 5 % and 12.6 % (Karlsson 1980) with the highest occurrence of loosening in the maxillary anterior teeth (Cheung *et al.,* 1990).

Goodacre *et al.,* (2003) reported that the three main problems following fixed prosthesis construction were caries (18%), endodontic problems (11 %), and loss of retention (7 %). However, loose retainers in conventional fixed prostheses with full coverage retainers were difficult to determine and diagnose. This was reported in work that showed that 12.6 % of the patients had undiagnosed loose fixed prostheses retainers (Karlsson 1986). This is in broad agreement with the observed loss of retention in fixed prostheses rather than in single crowns i.e. 7% versus 2% respectively (Cheung 1991; Walton 1999). Karlsson (1986) however also noted that a loose retainer occurs more frequently if the abutment had been root canal treated.

There are many factors that could influence the feasibility of removing a definitely cemented fixed bridge as been mentioned by Curtis *et al.,* (2006) including; the accessibility of the restoration, the condition of the abutments and the experience of the clinicians. This author recommended that abutments with loose retainers be critically evaluated prior to initiating crown removal procedures.

If a bridge is showing signs of failure many factors could influence the removal of a fixed retainer depending whether it is in the mandibular or in the maxillary arch. A high degree of planning was required prior to removal in 40% of the maxillary fixed retainers and 57% in the mandible (Curtis *et al.,* 2006). The explanation for this is that, the mandible is mobile and difficult to control while attempting retainer removal. In contrast, the maxillary arch is stable and fixed which makes for relatively easy retainer removal.

A number of factors were difficult to control while attempting to remove the fixed retainer; the amount and direction of force applied, the availability of instruments to be used for removal, the type of luting cement, the adaptation of the retainer casting and its associated amount of retention, the axial surface parallelism, and patient cooperation with the procedure. Fracture of porcelain margins and damage to the prepared tooth are some of clinical complications that might happen during an attempt at fixed prostheses removal (Curtis *et al.*, 2006).

Some of the methods that can be used for fixed bridge removal include; extraction forceps, haemostat, pliers, mallet and chisels (Oliva 1979). Subsequently the same author conducted a clinical evaluation study to assess the effectiveness of the Richwill removers for removal of 536 restorations including fixed-bridgework of three or more units. Rich will crown and fixed bridge remover consists of a resin base pliable substance, which become strong temporary adhesive under compression. It is positioned on the occlusal surface of the crown, which needed to be removed, and is compressed with firm finger pressure to adhere it to the surface of the crown. The patient is requested to close into the remover to compress the two-third of its bulk. The force for crown or prostheses removal is generated by closing and opening of movement of their jaw.

Oliva (1979) concluded that successful removal of a retainer occurred in only 72% of permanently cemented fixed prosthesis. However, there was 100% success in the other groups consisting of complete single crowns, ¾ crowns in comparison to fixed prostheses (Oliva 1980). The author also noticed that the use the Richwill remover requires good professional judgement and proper patient evaluation where the opposite teeth and their restorations must be firm and sound, if not, the result could be the removal of the opposing tooth's restoration rather than the fixed bridge. The reasons for unsuccessful removal of fixed bridges were; too long and parallel axial walls, excessive rough and ledges axial surface, direction of prosthesis removal at an acute angle to the long axis of the tooth, lack of co-operation of the patient. Although these studies have less scientific validity than a controlled trial, they can still provide useful data for comparison in the absence of other studies.

Other methods of removal have been described including the use of a restorative matrix band, a rubber dam clamp, a wire loop and lever and the use of acrylic resin to protect the ceramic layer (Verrett and Mansueto 2003). Few studies have outlined the complications associated with attempted removal of cemented fixed prostheses retainers. Curtis *et al.*, (2006) described methods including use of a matrix band, a haemostat, a Richwill crown remover, ultrasonic and pneumatic crown removers. These however, could result in fracture of porcelain margins or damage to the abutment retainer. Oliva (1980) concluded that the use of Richwill crown and fixed bridge remover is very helpful in the removal all types of cast restorations. It is easy reliable method to use and it seems to be minimal trauma to the teeth and restorations. Other techniques for removal of fixed prostheses have included the use of a wire and loop as a class 1 lever. Removing cemented fixed restoration requires forces applied carefully in the direction parallel to the path of insertion (Conny and Brawn 1981). Graver and Wiser (1979) used auto-polymerized resin painted onto the facial and lingual surface of a crown to create undercuts that can be engaged by a crown puller. A modification of this approach has been described by Liebenberg (1994) creating a retentive pit in the facial surface of the restoration to facilitate addition of a resin coping, with the subsequent defect in the crown being repaired with composite resin.

Preventing damage to the teeth and surrounding tissues is the most important consideration in removing the fixed bridge safely. It may be possible to re-cement the bridge provided that the cause is identified and eliminated and, following recementing, the occlusion should be re-checked.

Preserving the supporting abutment teeth is the primary objective when removing the prosthesis and although it is reasonable to attempt to remove a fixed prosthesis intact and one must be aware of several factors may that influence the like hood of this occurring.

Factors that which should be considered before any efforts to remove the restoration; location of the bridgework, the number and condition of the abutments, and the type of retainers used (Conny and Brown 1981).

Cementation failure (leading to loosening of a retainer) is one of the most common clinical complications of fixed prostheses. As noted earlier, retainer failure is a challenging situation when cements fail under a fixed retainer while another retainer is still cemented (Verrett and Mansueto 2003). In this case, the prosthesis should be removed in order to prevent recurrent caries and minimise the risk of mechanical damage to the abutment tooth.

If a fixed prosthesis retainer loses its retention there are several treatment options; one is to remove the retainer, if it is intact as well as the abutment, and re-cement it with more rigid cement. However, before this is performed it is important to diagnose the cause of failure, and rectify any shortcomings, to prevent the same mechanism of failure from arising after recementation.

Another option is to section and remove the prosthesis and to consider a new bridge. However, this is at the expense of fabricating a new bridge. However, the attempt to remove the cemented retainer can also result in damage to the abutment tooth itself so that construction of a new bridge is not feasible.

2.5.3.2 Failure due to Post and core

The endodontic treatment of pulpless teeth often results in loss of tooth strength, and the tooth becomes weak probably because of reduction of dentine mass (Sorensen and Martinoff 1985; Christensen1996). Although there is, also the argument that the devitalisation of the tooth and processes involved in endodontic renders the dentine brittle, due to loosing moisture content compared with teeth with a vital pulp (Sedgley and Messer 1992). Because of this, crowning of such teeth is considered as an integral part of the endodontic therapy. One clinical study (Sorensen *et al.,* 1985) on teeth with posts concluded that there were 2 % less failures for incisors and above 30 % less failures for premolars and molars after crown coverage restorations (compared to uncrowned control teeth).

There is some argument about the necessity of post placement before prosthetic restoration. Some authors consider the placement of a post before prosthetic treatment as essential (Sapone and Lorencki, 1981; Kantor and Pines, 1977) while others consider that post preparation may further weaken the prepared tooth (Assif *et al.,* 1993). Therefore, post placement should only be used if it is required to increase the retention support of the fixed prosthesis and not to strengthen the endodontically treated tooth. The amount of remaining dentine height is also thought to be an important factor for fixed bridge longevity (Assif *et al.,* 1993).

Away from the fixed bridge situation, it has been reported that root canal treated teeth restored by posts have an increased survival rate if the post length is equal to, or greater than the crown length (Standlee and Caputo, 1993). This is in agreement with the study conducted by Sokol (1984) in which he reported that post length may impact on the survival rate of root canal treated abutment teeth.

The post diameter also has great impact on the failure rate of endodontically treated teeth used as abutment. Higher failure rates occurred for posts with small (ISO 50) and large (ISO 10) diameters, while a standard sized post (ISO 90) had the best clinical outcome (Wegner *et al.,* 2006). Recommendations regarding post diameter in the literature are controversial. Pilo and Tamse (2000) advocated that the retention of residual dentin is of utmost importance while Stern and Hirshfeld (1973) suggested that the optimal diameter of the post is one-third the diameter of the natural root.

The reason for the increased failure of post-retained bridges (*in-vitro*) is probably because of (Jacobsen 1983);

1. Inadequate root filling, post crown should not be provided for teeth whose integrity is in doubt i.e. lateral incisors.

2. Longitudinal root fracture, whenever a post is lost, the root must be carefully checked for a longitudinal fracture and this may caused by;

i. Over-preparation

ii. Excessive force used during preparation

iii. A short or ill fitting post

iv. Incorrect occlusion in functional movement

3. Lateral perforation

4. Recurrent caries of the root caries

Many studies have been undertaken to assess the success rate of post and core restorations (Creugers *et al.,* 1993). The survival rates of some of these studies were from 98.6%, after period more than 10 years in a retrospective study (Weine *et al.,* 1991) to 77.6% after a period of 5.2 years (Roberts 1970). Endodontic and restorative treatment must be aimed at preserving tooth structure to provide strength and resistance to fracture of root treated tooth.

In a clinical analysis of 2,000 bridge retainers, post retained crowns were found to have a higher failure (Roberts 1970). In addition, the mean life span of a post crown only 4.2 years and most of failures occurred within the first 3 years (Lewis and Smith 1988).

The hazards of placing an intracoronal post include; risk of root fracture during placement of the post, the possibility of root perforation while root preparation, the wedging action of tapered dowels (Sorensen and Martinoff 1985). Although post failure is sometimes re-treatable, vertical root fracture is usually untreatable and often ultimately leads to extraction (Morgano and Milot 1993).

The findings from clinical studies suggest that adherence to a standardised clinical protocol of endodontic employing: optimal aseptic conditions, rubber dam isolation, thorough chemo-mechanical disinfection, provision of temporary restoration between visits, a dense obturation technique, a > 3 mm length of gutta-percha remain after post space preparation are factors for high survival rates and less complications of root filled teeth used as abutments for fixed bridge construction (Goodacre and Spolnik, 1995).

"The objectives of post removal are that should be simple and the integrity of the remaining tooth structure should be preserved" (Machtou *et al.,* 1989). A common complication is the failure of endodontic therapy in the presence of an apparently successful post. Many authors believe that removing posts can lead to root fractures and this could be the main reason why most practitioners avoid this procedure. However, Abbott (2002) mentioned the use of Gonon, the Eggler and the Ruddle post removers were safely post removal. He studied the incidence of root fracture after removal of 1600 posts by endodontic specialist practice and reported only 0.06%.

An alternative solution is use peri-apical surgery to treat failed cases rather than attempting to remove the post. However, previous literature shows that the success rate of re-treatment is considered higher than for surgery (Allen *et al.,* 1989; Molven *et al.*, 1991). The most common reasons stated by American endodontists as indications for peri-apical surgery, instead of removing a post included; an intact post and crown, to avoid root fracture or perforation, a large/long threaded post, or a post that cannot be removed after reasonable effort (Stamos and Gutmann 1993).

The use of ultrasonic energy is a highly efficient method of removing of crowns and cements within the root canal space when re-treatment or rehabilitation of that space is planned. However, there are many factors that influence post removal such as post type, cementing agent and tooth morphology (Gluskin *et al.,* 2005). These factors should be considered carefully before start with any treatment (Ruddle 2004).

The objectives of post removal are that it should be "simple, expedient and the integrity of the remaining tooth structure should not be jeopardised" (Machtou 1980). Studies been conducted to evaluate post removal from the root treated canal and many techniques have been devised over the years in an attempt to safely and efficiently remove such posts. These include special burs, the use of ultrasonics, and Masserann kit (Williams and Bjorndal 1983).

2.5.3.3 Fracture of the porcelain veneer

If a piece of porcelain fractures off or the entire facing is lost, this may due to failure of the metal-ceramic bond and the problem can often be repaired with composite resin. However, it is less satisfactory than the porcelain layer and discolouring or surface wear may happen after few years (Smith and Howe 2007). In order to prevent this type of damage to metal-ceramic bridges, the framework must have an adequate thickness of metal to avoid distortion and produce a rigid pontic area to prevent metal flexing thereby present of fracture the porcelain layer. Fracture of the metal frame is a rare cause of failure due to the developments made in porcelain veneer materials, which makes it possible to incorporate bridges with a framework that can withstand the strain and functional load (Hammerle 1994).

A solder joint is one area, which may lead to mechanical failures under occlusal loading. This may be due to failure to bond to the surface of the metal. Too much restriction for soldered connectors can lead to inadequate area of solder and to failure. If this happens in a metal-ceramic bridge, it often means that the whole bridge would have to be removed and remade (Smith and Howe 2007).

To prevent fracture of porcelain especially with long pontic spans, adequate dimension of both the metal frame and the veneer porcelain should be provided (Erhardson 1983).

Occlusal wear and perforation are other mechanical failures that could happen in fixed bridges. Even with normal attrition, the occlusal surfaces of posterior teeth wear down over a lifetime. The gold may wear over a shorter period compared with non-precious alloys (Smith and Howe 2007).

In the results obtained by Nyman and Lindhe (1979) 0.21% (7 fractured fixed bridges /332) technical failure problem occurred over the entire observation period (from 1969 to 1973 in 332 fixed bridges). In contrast, Schwartz *et al.*, (1970) reported 7.4% of failures were due to wear of both acrylic veneer and gold occluding surfaces. Randow *et al.*, (1986) encountered 12% and Valderhaug (1991) 5.5% aesthetic failure partly due to a veneer problem.

The different results demonstrated the advantage of porcelain over acrylic with regard to longevity as the veneering material. The technical progress in porcelain veneering and improved manufacturing techniques has decreased the incidence of failures due to fracture of veneering porcelain. Therefore, acrylic veneers are no longer recommended in fixed prosthodontics (Hammerle, 1994).

2.5.3.4 Fracture of abutment teeth

When a tooth is used as an abutment and has been prepared to receive the retainer, the subsequent loss of tooth structure makes it more liable to fracture. In order to reduce the frequency of tooth fracture, as much dentine as possible should be preserved during preparation. However, an adequate space must be provided for the metal frame and veneer materials to prevent over contouring the retainers.

A review of literature has been shown that fixed bridges exhibit complications due to a wide range of factors. Goodacre *et al.*, (2003) identified tooth fracture as one of the possible fixed bridges complications. In this study fracture of an abutment toot occurred in 3% of prostheses.

In the review by Nyman and Lindhe (1979) 2.4% of abutment teeth fractured. Landolt and Lang (1988) demonstrated 3% fractures for vital teeth and 35% for root canal filled teeth. This in agreement with a study conducted by Randow *et al.*, (1986) and who indicated that root filled teeth show a higher frequency of root fractures. These authors explained the reason for this is that the dental pulp contributes mechanoreceptors that react to loading. In a study conducted by Randow and Glantz (1986), the authors concluded that the receptors in the pulp tissues react at lower forces than the periodontal receptors, thus protecting the tooth from harmful load.

However, it has been shown to be cause of failure few in approximately 4% of the failed post and core (Abbott 2002). The author studied the incidence of root fracture following removal of 1600 posts in a specialist endodontic practice and reported it to be only 0.06%. This may be due to unsuitable case selection, poor laboratory technique, poor or unsuitable design of post. Following a post fracture the remaining part of the post within the root canal can be difficult to remove and if it is removed further tooth substance is usually sacrificed causing weakening the tooth structure and leading to more chance of further root fracture (Fox 2007).

Fracture of a fixed bridge abutment adjacent to a cantilever has been reported to occur twice as frequently as fracture of an abutment not adjacent to a cantilever (Goodacre *et al.*, 2003). Verrett and Kaiser (2005) identified in a clinical report, that abutment teeth may fracture or the cement within a retainer can fail when subjected to excessive forces. Abutment fractures in conventional fixed bridges have been documented in longitudinal clinical studies (Valderhaug, 1991; Karlsson, 1986). In the study by Lindhe (1979) found that 2.4% of abutment teeth fractured. Dentine tooth structure should be preserved as much as possible during tooth preparation to receive fixed prostheses to reduce frequent tooth fractured.

2.5.3.5 Occlusion

The term occlusion is defined as the functional and parafunction and dysfunctional relationships between an integrated system of teeth, supporting structures, joints and neuromuscular components. It includes psychological and physiological aspects of function and dysfunction (Ramfjord and Ash 1971).

Functional occlusion means conductive to function and refers to state of the occlusion; in which the occlusal surfaces are free of interferences to smooth gliding movements of mandible. In addition, there is freedom for the mandible to close into maximum intercuspation in centric occlusion and centric relation.

The occlusion of teeth is the key to oral function and the way the teeth occlude in function is important for health and comfort of the masticatory system (Ramfjord and Ash, 1971).

Functional coordination of the occluding surfaces of the teeth is one of the most important factors in the practice of dentistry. The incisal guidance (which is the inclination of the lingual surfaces of the six upper anterior teeth) is considered as the key to functional occlusion (Schuyler 1953). He reported that, establishing the anterior tooth relationship, aesthetics, and incisal guidance should be the first step in planning any oral rehabilitation and if this not achieved the anterior teeth cannot resisting the stresses in centric and eccentric contact. This increases the possibility of more occlusal load/stress acting on posterior teeth, which could result pathologic changes to supporting tissues. The determinant of occlusion, which includes incisal and condylar guidance, the plane of occlusion and cusp height, has reported by Hanau (1964). In general, the magnitude of the occlusal forces was larger in posterior teeth than in anterior region (Lundgren and Laurell, 1986). Occlusal disturbances may be created iatrogenically by premature crowns and fixed prosthesis. Ettala-Ylitalo *et al.*, (1986) conducted a retrospective study consists of 147 subjects treated with fixed prostheses in a 4 year period, and concluded that occlusal interferences were found in 34.9% of the crowns and in 27% of the pontics. De-bonding occurred in 4.15% of the bridges examined in a study conducted by Cheung *et al.*, (1990) which was limited to the upper and lower posterior segments. Occlusal interferences appear to have been the major factors in de-bonding of these retainers, which were endodontically treated and restored with posts and cores. This result is in general agreement with that of Karlsson (1986).

Patients seeking restorative work generally have predisposing factors that produce occlusal interferences, and Karlsson noted that, this is because of tilted teeth and faulty restorations; therefore he suggested, prosthetic control of occlusion and masticatory function was mandatory in order to decrease the occlusal interferences and more attention should be paid to occlusion in fixed prostheses.

2.6 Resonance Frequency Analysis (RFA)

2.6.1 Introduction

Dental implants are being used to provide support and retention for prostheses replacing missing teeth in edentulous and partially dentate patients. The term osseointegration has been used to define a direct structural and functional connection between living bone and the surface of a load implant (Branemark, 1983). The implant is usually left unloaded for period of 3-6 months following placement in order to allow healing process to occur. The clinical manifestation of osseointegration of a dental implant is the absence of implant mobility (Albrektsson *et al.,* 1994).

The clinical measurement of dental implant stability and osseointegration is an important parameter to be able to assess success. Primary implant stability has been identified as a requirement to achieve osseointegration (Branemark *et al.,* 1977; Albrektsson and Linder, 1981).

Initial stability of an implant fixture at the time of placement is often important and it can be assessed by checking the presence of any mobility and bone quality (Lekholm and Zarb, 1985). Due to less hard tissue support, implants placed in bone of low density may have a reduced initial stability, which in turn may lead to less adequate integration in bone during healing phases (Sennerby *et al.,* 1992).

Clinically, it is possible that a dental implant may fail in a number of ways (Meredith *et al.,* 1996); e.g. as a result of trauma, infection, placement in compromised tissues (Type IV bone quality where the bone is less density) or in a heavy occlusion (uncontrolled load). The failure can manifest itself in a number of ways; by increasing mobility or loss of the implant, by a decrease in the height of the surrounding marginal bone or by fracture of one or more implant components.

To assess the quality of the implant /tissue interface clinically, the most non-invasive method available is radiography. This gives valuable information regarding the marginal bone condition around dental implants. Sunden *et al.,* (1995) emphasised the use of high quality radiographs for accurate diagnosis of peri-implant radiolucencies. They concluded that the probability of predicting clinical implant instability from radiographs was low in a population with low prevalence of implant mobility. However, one of the difficulties with radiographic techniques is that the use of a standardised technique is required to ensure good reproducibility.

Other widely used methods for clinical testing of implant quality and degree of implant stability include: percussion of the implant abutment with a blunt instrument such as a mirror handle, and trying to elicit any mobility by moving the implant in a bucco-lingual direction. There is little evidence in the literature to support the validity of these widely used clinical techniques.

Schulte *et al.,* (1983) reported that an electronic instrument (Periotest, Gulden, Germany) had been developed and designed to perform some measurements of the characteristics of the periodontal ligament surrounding the tooth and thus establish a value for its mobility. The Periotest comprised a hand piece connecting a metal "slug" which was accelerated towards a tooth measured by an accelerometer. The software in the instrument was designed to relate contact time as a function of the tooth. The result was displayed digitally and audibly on a scale of -8 (low mobility) to 50 (high mobility). This measures of a wide variety of natural tooth mobility and damping characteristics of bone-to-implant interfaces (van Steenberghe *et al.,* 1995). Readings were taken when the device registered the same value at three repeated times (Cranin *et al.,* 1998).

Many authors reported the potential applications of Periotest in measure implant mobility. Olive and Aparicio (1990) in a review of the literature described that typical Periotest values obtained when using the instrument was -5 to 5 for ITI implant system. A healthy implant surrounded by healthy bone will exhibit quite stiffness characteristics in comparison to a tooth supported by a periodontal ligament, hence the low Periotest values. However, the lack of resolution, poor sensitivity and susceptibility to operator variables of the Periotest has been criticised (Meredith, 1998).

Kaneko (1987, 1991) and Kaneko et al., (1986), have described a further non-invasive test method proposed for the integrity of the implant tissue interface. The technique used the application of a high frequency mechanical vibration to the implant under test. This method uses puncture needles, which penetrate the mucosa to transmit the signal to the implant and the resultant waveform, is measured. However, the sensitivity of test is noticed and the results suggested (Kaneko, 1991) that, the load applied to the implant will cause vibration of the bone itself.

In 1996, Meredith *et al.*, described *in-vivo* a non-invasive method by measuring the resonance frequency of a small transducer attached to an implant fixture to test the amount of bone formation around an implant by testing implant mobility. The principle of the method (Meredith *et al.,* 1996) was to attach a transducer either directly to the implant fixture or via a transmucosal abutment using a screw. The transducer was made from stainless steel or pure titanium and comprised a small metal beam to which 2 piezo ceramic elements were attached. The transducer vibrated by exciting one of the piezo elements with a signal, the response being measured by the second element. The transducer was excited by a frequency response analyser, which is programmed by a personal computer. The output from the response element was amplified by a charge amplifier.

Meredith *et al.,* (1997) conducted a study to test the practicability of using resonance frequency analysis to measure bone height and abutment length *in-vivo* and they concluded that resonance frequency measurements are related to the effective length of an implant above the level of the bone. They also mentioned that resonance frequency analysis may be used to monitor changes in stiffness and stability at the implant-tissue interface and could distinguish between successful and failed implants.

Implant stability is measured either by determining the resonance frequency of the implant – bone complex or by reading the implant stability quotient (ISQ) value given by the Osstell equipment (Integration Diagnostics AB, Gothenburg, Sweden).

Stability of the implants was measured based on the detection of vibration with a resonance frequency measurement probe. This has a magnetic material in the upper part of the instrument, which forms a magnetic field with the Osstell Mentor used to detect the vibration. Data collected are expressed as Implant Stability Quotient (ISQ). The ISQ value is based on the underlying and calibrated resonance frequency (RF) of the transducer and is given as a number from 1 to 100 where 1 is the lowest and 100 the highest degree of stability.

The ISQ has been found to vary from 40 to 80, the higher the ISQ, the higher the implant stability. A clinical study conducted by Nedir *et al.,* (2004) evaluated the Osstell as a diagnostic tool to identify a stable dental implant. They concluded that the repeatability of the Osstell equipment measurements was satisfactory and implant stability could be reliably determined for implants with an ISQ >47. The implants with a low ISQ value was considered as decreased implant stability, and for implants with high ISQ values, increase of implant stability. Sennerby and Meredith (2008) suggested that implants with a primary stability above ISQ 60-65 may be suitable for immediate loading, while implants below ISQ 40 may be more prone to failures.

2.6.2 History of Resonance Frequency Analysis (RFA)

The first generation RFA transducer (stainless steel or pure titanium) was a simple offset cantilever beam with two attached piezoceramic elements, which could be screwed to an implant fixture or abutment. The beam was vibrated by exciting one of the piezoceramic elements with a signal of varying frequency. A frequency response analyser that was programmed by a computer synthesized the signal. The second piezoceramic element measured the response of the beam and a charge amplifier amplified the signal generated. The signal is a sine wave of varying frequency from 5 to 15 kHz (Sennerby and Meredith, 2008). The resonance frequency values were greater than 7.10 kHz indicating high implant-bone interface stiffness (O'Sullivan *et al.,* 2000).

The disadvantages with the first generation of RFA included a large cable, the bulk and weight of the equipment, the cost, and the sweep time of the frequency response analyzer.

The second generation of RFA instrument was established and it was designed to be relatively easy to use, program and to download data from. It was portable and lightweight, safe for patient use, and could be used in conjunction with a personal computer that could set the frequency sweep and collect and store data on the hard disc. However, there were still some major disadvantages such as: each transducer had its own basic resonance frequency and this had to be calibrated before measurements could be were compared. Moreover, interpretation of the results was not possible with the patient, at the chair side. Furthermore, the system (instrument and computer, cabling) was too heavy to be portable for clinical use.

A further development of the resonance frequency analysis system, the Osstell Mentor (Fig16) (Osstell; Osstell AB, Gothenburg, Sweden) consisted of a rechargeable, battery-driven frequency response analyser and new design of transducer (probe) that was calibrated at source by the manufacturer. This device was designed to be portable and easily used at the chair side.

The result of the measurements was expressed in a more comprehensible parameter (implant stability quotient - ISQ) rather than in a frequency sweep spanning 5 – 15 KHz. The ISQ unit, based on resonance frequency, ranges from 1 (lowest stability) to 100 (highest stability). The different implant systems and abutments have different transducers which allowed all resonance frequency analysis measurements to be directly compared. In addition, all results were transferrable to a computer for further analysis and storage. The readout on the device allowed the operator and patient to receive instant feedback on the results.

The most recent version of the RFA device is wireless, where the probe is directly attached to the Osstell Mentor (Figure 13). A metal "Smartpeg" is connected to the implant or abutment by means of a screw connection. The Smartpeg has a small magnetic head attached to its top, which is excited by magnetic pulses from the probe of the Mentor. The peg vibrates in two directions perpendicular to each other. The first mode direction gives the highest resonance frequency and the second mode direction gives the lowest resonance frequency. For example, an implant with palatally exposed implant threads may show one low value, indicating the lack of bone in the bucco-palatal direction, and one high value indicating good bone support in the mesio-distal direction.

2.6.3 Principles of RFA

In sound applications a resonant frequency is a natural frequency of vibration. Any object can vibrate at its resonant frequencies (each object has many resonant frequencies) and hard to get it to vibrate at other frequencies. It can pick out its resonant frequencies from multiple excitations and vibrate at those frequencies by filtering out other frequencies present in the excitation (Serway 1996).

Different types of resonant frequencies exist (Cawley 1985) are the acoustic resonance of musical instruments (string instruments, wind instruments), orbital resonance (An orbital resonance occurs because of two orbiting bodies apply a constant gravity influence on each other).

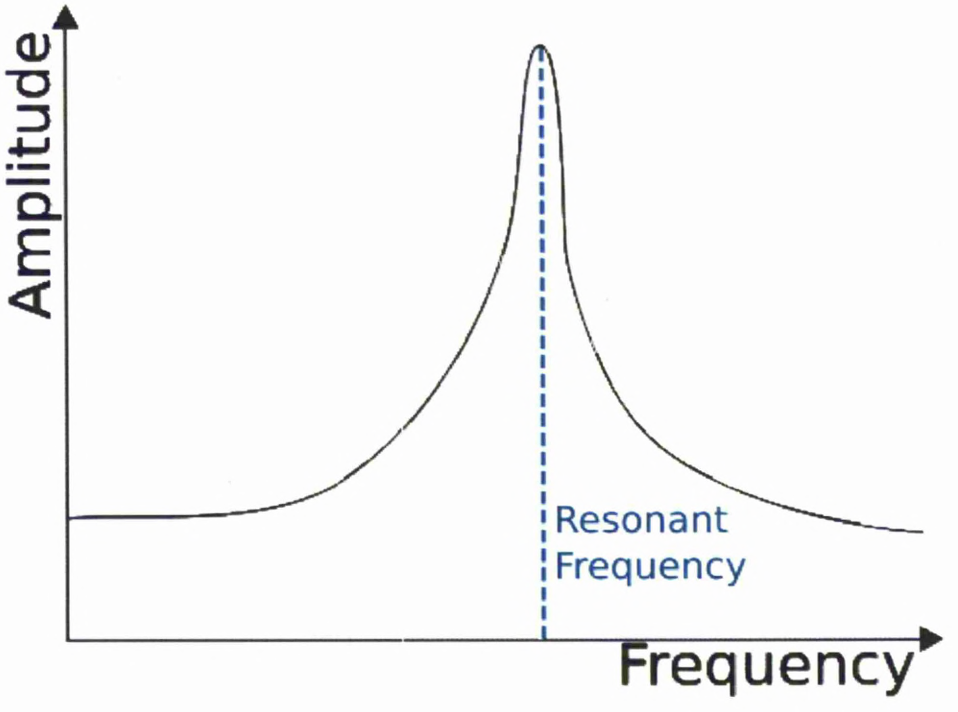
Acoustic Resonance, in physics, is when there is an increase in the oscillatory energy of an object in response to another object's vibration. This oscillation is maximal when the objects both have coincident or similar, inherent natural frequencies of vibration. The vibration response can be measured and displayed as a frequency reading from which the natural frequencies of the component can be extracted and appeared on the its screen which is interpreted as resonance frequency (Cawley, 1985). A review paper by Adams and Cawley

(1985) reported that many investigations have shown that the natural frequencies of a component/object are being likely to be reduced by damage in one of these components while the vibration damping is increased.

One example of resonant frequency can be seen, and heard, in acoustic frequencies of musical instruments. The sound from a stringed instrument is produced by vibrating strings and this usually produces a sound of a constant frequency when one note is played. The frequency of the note produced depends on the length of the vibrating part of the string, the tension of each string and the excitation point. If a note is played on one string that corresponds with the natural frequency of a second string, that second string will "resonate". This is the principle of "sympathetic strings" found on some instruments (e.g. Giter).

Frequency can be defined as the number of times that a repeated event occurs per unit of time. This is therefore calculated in means of Hertz, where 1 Hz is an event repeated once per second (i.e. 1 cycle per second). The frequency of sound or electrical signals is measured in Hertz, i.e. the number of cycles of the repetitive wave or frequency form per second.

Figure 1 Diagram to illustrate resonant frequency of an object (after Serway 1996)



The Osstell equipment uses the Mentor probe to generate an impulse close to the magnetic head of the Smartpeg. This magnetic field excites the magnet and causes the Smartpeg to resonate at high frequency. The Smartpeg (the resonant object) is manufactured with a given length and density to have one main resonant frequency and so it will vibrate mainly at this frequency in response to multiple excitations from the Mentor probe (although other minor frequencies may also be present).

The multiple frequencies produced by the vibrating object (Smartpeg) are then analysed by the Osstell Mentor. The relationship of the Smartpeg's resonance to the natural frequency of the probe impulse is analysed by Osstell software and displayed in a simplified form as Implant Stability Quotient (ISQ) values in the case of dental implants. The software analysis allows the resonant frequencies to be recorded as ISQ values from 0 (low implant stability) to 100 (high implant stability).

The clinical application of the ISQ value is that a high reading indicates the dental implant is stable while a low reading indicates that this dental implant is at risk and further observation is needed in near future.

The Smartpeg vibrates in two directions perpendicular to each other. The first mode direction gives the highest resonance frequency and the second mode direction gives the lowest resonance frequency. For example, an implant with palatally exposed implant threads may show one low value, indicating the lack of bone in the bucco-palatal direction, and one high value indicating good bone support in the mesio-distal direction (Meredith *et al.,* 1998a).

The length of the Smartpeg being assessed is important, as any changes in this will affect the resonant frequencies (as would happen by shortening a string on a musical instrument) and therefore, the ISQ reading could also change. The calibration of the instrument therefore requires the use of a Smartpeg of fixed length. A high ISQ (≥ 70) indicates that the dental implant does not move when the Smartpeg is excited by the Mentor Probe. However, if the dental implant is not stable in the surrounding bone, it moves along with the Smartpeg. This changes the effective length of the Smartpeg, alters the resonant frequency, and will affect the ISQ reading with a lower value displayed on screen.

2.6.4 RFA to predict implant failure

In-vitro studies have been used to measure changes in mechanical properties and stiffness to represent those occurring in bone during remodelling and healing around an implant fixture. A resin polymerization model been used to evaluate these time-dependent changes in stiffness. A significant increase in stiffness during polymerisation of a resin as it cures to a solid phase is detectable using RFA (Meredith *et al.,* 1996).

Resonance frequency analysis techniques have also been used in animal studies. This has recorded increasing values with time as more stiffness is obtained from new bone formation and remodelling (Meredith *et al.,* 1997).

The Osstell technique has shown higher implant stability in mandibular bone than in maxillary bone (Bischof *et al.,* 2004; Ostman *et al.,* 2005).

Friberg *et al.,* (1999) used RFA measurements to evaluate 75 one-stage implants that had been placed in the mandible. These authors observed that, a small number of implants after few weeks of insertion, showed a decrease in stability. These implants were also found to be clinically mobile. However, these implants subsequently increased their stability after the patients stopped wearing their dentures. Glauser *et al.,* (2004) in an immediate retrospective study, evaluated 81 implants from placement to one year in function. All implants showed a high initial stability of around an ISQ value of 70. But, after 1 month of immediate loading some implants showed ISQ values of 49-58 indicating a higher risk of future failure. Sjostrom *et al.,* (2005) reported lower implant stability for 17 implants (ISQ 54.6) that failed within the first year of function while 195 implants (ISQ 62.0) successfully integrated in the maxilla. However, Nedir *et al.,* (2004) concluded that the RFA technique was not reliable to identify mobile implants, when they compared immediate-loaded implants with implants loaded after 3 months. This could be because the nature of RFA technique measures the stability as a function of stiffness. When a dental implant shows clinical mobility, this is means that ISQ values decrease and display low stiffness (Meredith *et al.,* 1998).

2.6.5 Possible clinical implications of RFA

The RFA technique has the reliability to detect clinically stable implants and to give relevant information about the state of the implant-bone interface during the different stages of the treatment. Implant success has been shown in many studies to be influenced by the quality and quantity of bone at the implant site (O'Sullivan *et al.,* 2004). Sennerby *et al.,* (1991) demonstrated a correlation between the amount of cortical bone and removal torque and concluded that dense cortical bone can provide better implant stability than cancellous bone.

Although the failure rate of implants used in two-stage procedures is low, it is evident that higher failure rates are associated with immediately loaded and grafted implants and/or more implants placed by relatively less experienced clinicians (Sennerby 2008). Meredith *et al.,* 1998 have also demonstrated that high values obtained by resonance frequency analysis are indicative of successful implant integration with low risk of failure. Conversely, low or decreased resonance frequency analysis values indicate an increased risk of implant complications. A low RFA value after implant loading may indicate disintegration of implant-bone interface and progressive failure. Unloading of the implant might then be performed in order to improve the stability of the fixture. Furthermore, a decreasing implant stability quotient value can be as a result of ongoing marginal bone resorption and radiographs should be use to assess the status of supporting tissues (Sennerby and Meredith, 2008).

The resonance frequency analysis technique may used in follow-up examinations of implants. One of the disadvantages in using the RFA technique is that prosthetic constructions and/or abutments on the implant need to be removed in order to make the measurements which, in some cases, are not an easy task.

RFA may be useful for assessing immediate loaded implants through different stages of treatment. Ostman *et al.,* (2005; 2008) found that an ISQ value 60 can be used as an inclusion criteria for immediate loaded implants in the edentulous maxillae and in the posterior mandible. Sennerby and Meredith (2008) reported that the resonance frequency analysis technique may also provide indications as to when to replace immediate temporary prostheses with permanent prostheses after implant placement. They suggested an ISQ value of 60 as an indicative response for immediate loading.

The resonance frequency analysis technique may act as a valuable means for monitoring objectively clinical outcomes results of implant treatment which in turn can be important medico-legally. It can be reassuring the referring clinician and the patient that there is sufficient implants stability before commencing any prosthetic construction.

2.7 Periotest

Aparicio (1997) used the Periotest to measure implant stability in 1182 Branemark implants and found that there was a direct correlation between Periotest values (PTV) and the degree of osseointegration. Another study, including a large sample size (2,900 implants) showed similar results, irrespective of implant design, diameter, length and bone quality (Walker *et al.,* 1997). Data on using the Periotest device reported that it can be one of the objective clinical measurements of the stability of bone implant interface (Walker *et al.,* 1997).

The Periotest values (PTV) are influenced by excitation conditions such as position of the hand piece and its direction. During the measurements of PTV, the hand-pieces should be held in a mid buccal direction and perpendicular to the tooth axes (Schulte and Lukas, 1992).

The PTVs of clinically Osseointegrated implants in studies (Morris *et al.,* 2003; Teerlinck *et al.*, 1991) vary between -4 to -2 or -4 to +2 therefore these values may have a small standard deviation and may be incorrectly interpreted as the Periotest having a high degree of accuracy.

However, the dynamic range used for measuring implant mobility is limited and the device is not sensitive enough to measure implant mobility. Most studies of the use of the Periotest (designed to measure the mobility of a natural tooth), to measure implant mobility have reported a lack of the sensitivity of this device (Meredith *et al.,* 1998). It has been recorded that PTV cannot be used to identify a borderline implant which may or may not be Osseointegrated (Hurzeler *et al.*, 1995).

Limitations of Periotest measurement have been suggested to be related to the excitation source or the striking point. The *in-vitro* and *in-vivo* experiments reported that the influence of the striking point on PTV may be affected through changes in implant length, angle of the hand piece or repercussion of a rod (Meredith *et al.,* 1998; Derhami *et al.,* 1995) where control of these factors is very difficult.

The prognostic accuracy of PTV for implant stability has also been criticised for a lack of resolution, poor sensitivity and susceptibility to operator variables (Salvi *et al.,* 2004). The Periotest may, however, be used to evaluate stability of an implant with advanced bone loss but it often fails to detect/diagnose an implant with progressive bone loss because the values associated with this do not change until the bone loss is virtually complete (Cranin *et al.,* 1998).

One of the difficulties in using Periotest device is its pen grip hand piece which is simple to use interiorly, but difficult in posterior teeth due to access being limited by the buccal mucosa (Derhami *et al.,* 1995).

A further limitation, which also applies to the natural tooth, is that PTVs reflect displacement amplitude of the tooth on impact loading and these values do not reflect the overall periodontal tissue conditions (Hayashi *et al.,* 2010). The tapping action by the device may also be harmful to the tested object. This was one of the major reasons that it was not considered as one of the methods for detecting fixed bridge stability in the present study. The use of the Periotest device must be in a perpendicular direction to the lateral surfaces of the tooth or implant. This also reduces its utility.

3 THE RETROSPECTIVE STUDY

3.1 Introduction

In chapter 3, the literature regarding the clinical performance of fixed prostheses and resonance frequency analysis was reviewed. This chapter will consider retrospective data regarding the clinical performance of fixed prostheses derived from case notes. Different factors that may contribute to the failure of fixed prostheses are considered.

3.2 The aims and objectives

The present, retrospective, service evaluation aimed to record the clinical performance of different types of conventional fixed prostheses used to replace missing teeth.

This retrospective aimed to:

1. Determine the long-term survival rates of these fixed prostheses.

2. Determine the factors that caused these fixed prostheses to fail. These failures may be due to mechanical and/or biological complications. Mechanical complications were defined as; fracture of lute cement or loss of retention, failure of post and core, fracture of the abutment, fracture of the veneering material, fracture of bridge framework. Biological factors were defined as; dental caries development, loss of pulp tissue vitality and/or apical pathology (via radiograph), periodontal disease and increased tooth mobility (due to periodontal problems and loss of bone support).

3.3 Materials and methods

This aspect was carried out retrospectively from case-notes that been identified from the appointment books of two Restorative Consultants clinic. These case notes were selected due to involving fixed prosthesis failure or bridge complications. The cases notes were then obtained from case note library at Liverpool Dental Hospital and were subsequently reviewed according to previous selected criteria for inclusion in this study.

3.3.1 Case-note selection

From clinical diaries, between Jan 2004 – Dec 2008, one hundred and twenty two patients selected from referred cases to two Consultants at the Department of Restorative Dentistry at Liverpool Dental Hospital, specifically for the treatment of problems relating to fixed prostheses were identified. The case records were obtained from the patient case-note library and assessed according to the following criteria.

3.3.2 Inclusion Criteria

a. The case notes listed on two consultants working in the Restorative Department at Liverpool Dental Hospital (Dr AJ Preston and Prof CC Youngson).

b. The case notes contained a referral letter to Liverpool Dental Hospital.

c. The case notes identified that the patient had at least one conventional fixed bridge prosthesis is fitted.

d. The case notes included a radiograph(s) of the bridgework.

3.3.3 Case notes details

The detailed informations were taken from selected case-notes, and the following data were recorded on information sheet that consists;

- Case note number (no names to ensure patient confidentiality), age and gender of the patient
- design of fixed prostheses,
- presence of radiographs (to help in diagnosis of dental caries and apical pathology)
- location of fixed prostheses,
- presence of dental caries in the abutment teeth,
- loss of retention,
- presence of post crown,
- presence of apical pathology (on radiograph),

- occlusal problems,
- time since prosthesis fitted,
- mobility,
- fracture of ceramic.

3.4 Results of a retrospective study

The total of 143 case notes were selected from the appointment books that been marked as concerning fixed prostheses or “crown and bridge”. The case notes were collected and checked for the suitability for selection criteria. Each set of case notes were evaluated for information noted above. 120 case notes were considered suitable, the other 23 case notes having incomplete data.

The selected cases-notes were evaluated and the information collated into a data collection sheet for interpretation.

3.4.1 Age and Gender

On examining the demographic data in the case notes arrange of 20-77yrs was noted as recorded as shown in Table 1. The gender was 73 Female and 47 male from the case notes.

Table 1 Age distribution

16-25	26-40	41-55	56-70	71-85
3	4	55	46	4

3.4.2 Bridge Location (Maxilla and Mandible)

One hundred and fifty-five (n= anterior 123 and 32 posterior/168) (92.3%) of the bridges were in the upper jaw. The design and distribution of all the bridges are summarised in Table 2. Irrespective of location, the fixed-fixed design was the most common (n=131/168, 77.9%), whereas cantilever bridges constituted 19.0% of the total (n=32/168). Resin-bonded bridges (RBBs) were the least frequently used and formed only 2.9% (5/168) of the total percentage.

In the mandible there were 13 (13/168, 7.7%) fixed-fixed bridges in total fitted as shown in Table 2. However, there were no cantilever bridge designs fitted in the lower arch.

3.4.3 Position of the bridge (Anterior and posterior)

One hundred and thirty (130/168, 77.4%) of the total bridges (all designs) were in the upper and lower anterior region. Of these, 123 (73.2%) were constructed in the anterior maxilla and only 7 (4.1%) in the mandibular anterior region as shown in Table 2.

Table 2 Distribution of different bridge design

	Maxilla			Mandible			Total bridges
	Anterior	Posterior	Total	Anterior	Posterior	Total	
Fixed-fixed bridge	92	26	118	7	6	13	131
Cantilever bridge	26	6	32	0	0	0	32
Resin-bonded bridge	5	0	5	0	0	0	5
Total	123	32	155	7	6	13	168

The 123 upper anterior bridges (73.2%) constituted the most common position. Ninety-two (92/123) of upper anterior bridges (74.7%) used a fixed-fixed design. Anterior cantilever bridges accounted for 26 bridges (26/123) (21.1%) and the least common form of bridgework were RBBs (4%) as shown in Table 2. Fixed-fixed bridges were the only design used in the lower anterior region for the 7 bridges placed.

The total number of bridges replacing posterior teeth (in maxilla and mandible) were 38 (22% of the total bridges referred), out of which 32 (84.2% of posterior bridges) were of fixed-fixed design and 6 (15.7%) were of a cantilever design.

3.4.4 Bridge units

The total of 168 bridges involved 480 bridge units as identified from the case notes as in Table 3. These included 52 (52/168, 30.9%) post and core as shown in Table 7. Forty-three

(43/52, 82.6%) of these post units were used as an abutment and were included in a fixed-fixed design.

Table 3 Bridge unit distribution

	Anterior	Posterior	Total
Maxilla	335	95	430
Mandible	19	31	50
	354	126	480

Of the fixed bridge units, 73.7% (354/480) were fitted in the anterior region (maxilla and mandible) and 75.4% of the posterior units (95/126) replaced upper posterior teeth (Table 3).

3.4.5 Bridge design

All bridge work was cemented onto an abutment. Irrespective of location, the most common bridge design 77.9% (131/168) was the fixed-fixed; the cantilever bridge was then accounted for 19%.

3.4.5.1 Fixed-fixed design

Fixed-fixed bridge was the most common bridge design 58.9% (99/168) in the anterior segment, whereas the cantilever bridge design contributed only 22.6% (38/168) as shown in Table 2. In addition, upper anterior fixed-fixed bridge was 74.7% (92/123) when compared to upper posterior fixed-fixed design which was 21.1% (26/123).

3.4.5.2 Cantilever bridge design

Table 2 shows that the cantilever designs irrespective to their location contributed 19% (32/168) of total fixed bridge design. Out of these 81.2% (26/32) were placed in upper anterior teeth and 18.8% (6/32) of them replaced upper posterior teeth.

3.4.5.3 Resin-bonded bridge (RBBs)

The least frequent bridge design used was resin-bonded bridge design. The percentage of RBB was only 2.9% (5/168) and all of them were fitted in the upper anterior region.

3.4.6 Duration of bridges

The longest service of the different bridge design was 27 yrs and the range of longevity of fixed-fixed design was from 4 yrs – 27 yrs of an average of 23 yrs as in Table 4.

Table 4 Fixed-fixed bridge

Duration	5yrs	6-10	11-20	21-27
Number of bridges	18	15	10	3

The range of longevity for cantilever designs was from 3 months up to 120 months, with an average of 117 month duration as demonstrated in Table 5.

Table 5 Cantilever bridge

Duration	0 – 1yrs	1yrs-5yrs	6 -15 yrs
Number of bridges	1	7	2

3.4.7 Causes of fixed bridges failure

A “failed” bridge means that the bridge is no longer in situ, (identified as such from the case-notes.

The different causes of fixed bridge failure were also recorded. Table 6 shows a total of 61 (61/168, 36.3%) of all fixed bridges fitted had failed and 24 (24/168, 0.14%) of bridges were failing.

The failure rate was 1.54% per year (calculated according to Roberts 1970).

The mean life span of these bridges was 13.6 yrs ranging from 3 months up to 27 (324months) years.

Table 6 Distribution of failed and failing bridges

	Maxilla		Mandible		Total
	Anterior	Posterior	Anterior	Posterior	
Failed bridges	28	10	2	21	61
Failing bridges	20	3	0	1	24
Total failed and failing bridges					85
Failed posts	43	5	1	3	52

3.4.8 Mode of failure

From the case notes some factors contributed to the fixed bridge failure.

The most frequent cause of failure was associated with a post and core abutment. This happened in a total of 30.9% (52/168) of all the referred bridges.

In some cases the failure was due to more than one factor; such as a post problem associated with dental caries as well as apical pathology (or radiolucencies as shown on the radiograph) or loss of retention. In 32 (32/52, 60%) cases with a post problem there was also apical pathology and, in 19 (19/52, 36.4%) dental caries.

3.5 Discussion of the retrospective study

In restorative dentistry both technical and biological factors play important roles in the survival and failure of the bridge restoration and these factors should be considered while planning and making the bridge work.

The present retrospective study was aimed to investigate the success and the failure rate of different designs of fixed bridges referred to Restorative Department of the Liverpool Dental Hospital at The University of Liverpool over a period from Jan 2004 to Dec 2008.

In this retrospective investigation, biological and/or mechanical factors were recognised that contributed to failure. The failures of these bridges were multi-factorial. Mechanical failure e.g. associated with a post and core in the abutment tooth may be combined with dental caries development, and/or endodontic failure, and/or apical pathology. These combinations may contribute to loss of retention and subsequent failure of the fixed bridge. Often however, there were difficulties determining the primary cause of failure (biological or mechanical) as they were often interrelated i.e. loss of retention (fracture of lute cement) may have initiated dental caries of the abutment, subsequent pulp involvement leading to apical pathology (if not treated). Alternatively dental caries may have caused destruction of abutment structure that subsequently led to loss of retention of the fixed bridge.

The failures in the present retrospective study were identified as biological in origin; although these may be have been the result of an earlier technical error.

3.5.1 Age and gender

In the current investigation 60% of the referred patients to the Liverpool Dental Hospital were women, which is in agreement with the finding or result of other studies where more women than men seek dental treatment (Schwartz *et al.,* 1970; Valderhaug and Karlsson, 1976; Karlsson, 1986; Hochman *et al.*, 2003).

There appeared, in the current study, to be an association between the age of the patient and the rate of failure. More women had failed bridges 82.2% (60/73) than men 48.9% (23/47). In this investigation the average age was 55 (41-70), which may give an indication that high failure rate occurred in older women. Helkimo *et al.,* (1987) found a significant failure rate in elderly men may be due to occlusal forces. The causative factors related to a high failure rate have been discussed by Torbjorner *et al.,* (1995) in elderly may be more dentine brittleness and more teeth with repeated restorative treatments. .

Roberts (1970) found that there was a relationship between the age at placement and years of bridge in service. The author mentioned that the possible reasons for the unacceptable failure rate in patients in the under 20-years age group are short clinical crown length and high dental caries rate. However, subsequent improvements in oral hygiene and use of fluoride may explain the lack of relationship between the age of the patient and years in service in the current retrospective service evaluation.

The expected life span of fixed-fixed bridges in this study was from 6 to 15 years, which is in agreement with other studies that have reported a range of life spans from 2 to 11 years (Roberts, 1970; Schwartz *et al.*, 1970; Leempoel *et al.,* 1995).

3.5.2 Bridge position (anterior and posterior)

Anterior teeth are more prone to suffer pulp death because of their relatively large pulp size and the deeper and more extensive tooth reduction required to accommodate porcelain and metal in metallo ceramic bridgework. This trend was observed in a retrospective service evaluation where 73.6% (28/38) of the possible endodontic failures were in the anterior teeth (and all these abutment teeth, by definition, had bridge retainers). A similar result has been noted by Cheung *et al.*, (1990) where 70% of the endodontic failures occurred in anterior teeth. The negative influence of non-vital abutments has been reported by Leempoel *et al.,* (1995) where this tends to decrease fixed bridge survival rates with the presence of posts and cores being another contributing cause of failures (Hochman *et al.,* 2003).

In a previous study it has been observed that the anterior retainer became loose more often (41%) than a posterior retainer (32%) (Curtis *et al.*, 2006). Cheung *et al.*, (1990) reported that the post failure rate was significantly higher in the upper, and more in anterior teeth and this is in agreement with work result by Torbjorner *et al.,* (1995). It has been suggested that the anterior failure may be because of the dislodging force acting in a horizontal direction. The results of the current study were similar, where the majority of failed and failing fixed bridges 61.1% (52/85) and 75% (39/52) of posts were fitted in the upper anterior teeth.

3.5.3 Bridge designs

The results show 50.6% (85/168) of total conventional bridges referred were failed or failing bridges and the remaining of 83 (83/168) were considered as surviving bridges.

The failed bridges were due to biological and/or mechanical reasons, and the collective failure rate was 1.54% per year as calculated according to Roberts (1970).

The average life span of these bridges was 13.6 years, ranging from 3 months up to 324 months. The current results were similar to work results by Schwartz *et al.*, (1970) and by Walton *et al.*, (1986).

It has been proposed that the success rates of cantilever bridges is less, even in reduced occlusal forces than for fixed-fixed bridges designs (Pjetursson *et al.,* 2004). These authors reported that the estimated survival rate of conventional fixed-fixed bridges was 89.2%, and for cantilever bridges after 10 years was 81.5%.

Cantilever bridges in general are more conservative to tooth structure, easier to prepare (less alignment required), use fewer laboratory materials and involve less cost to the patients (Botelho *et al.,* 2000). Several studies investigating the failure rate of cantilever bridges have however revealed that these bridges fail more and at a higher rate than fixed-fixed bridges (Karlsson, 1986; Walton *et al.,* 1986). In the current investigation the total cantilever bridges were only 32 (19%) of the total bridges placed in both jaws and so the failure rate of these bridges was not clearly inferior to other designs.

3.5.4 Causes of bridge failures

Because there was limited written data and some information was missing from the case-notes there was difficulty determining the different causes of failure of fixed bridge in some case-notes. However, the biological and mechanical reasons that were identified as contributing to failure of the bridges are discussed separately in the following paragraphs, though some of these factors are inter-related and often many factors contribute to the failure.

3.5.4.1 Biological failures

Biological reasons for failure included; dental caries development, pulpal disease, and apical pathology. Radiographs were used to help in diagnose of dental caries, periapical pathology and the condition of any post involved in the bridge.

A retrospective evaluation of fixed bridge work by Walton *et al.,* (1986) demonstrated that 22% of total biological failures were caused by caries development after several years in function. Similar results were found by Randow *et al.*, (1986) where 25% revealed biological failures caused by carious lesions in bridges with 7 years of service.

3.5.4.1.1 Dental caries

Dental caries was the one of the highest causes of failure (14.8%) in the present retrospective service evaluation. This is in agreement with other studies (Kantorowicz, 1968; Schwartz *et al.*, 1970; Walton *et al.,* 1986; Hochman *et al.,* 2003). In this context, the current findings support the recommendation of Hochman *et al.,* 2003 where they suggested that more attention to identify high risk caries patients and concentrate on dietary advice and caries preventive measures would be beneficial to patients receiving bridgework. However, in this study dental caries was not considered to necessarily act alone in causing failure of fixed bridges as it could act in combination with other biological causative factors.

Goodacre *et al.*, (2003) reported that the most common complications following fixed bridge treatment were dental caries (18%), endodontic treatment (11%), and loss of retention (7%). Again, similar findings were observed in the current study where 15% of failure was due to caries and 11% loss of retention. However, loss of post retention was considered to be the principle causative factor of failure with caries considered to be a secondary reason for failure.

There are two types of carious lesions may affect the longevity of the fixed bridge work. First, caries may develop at the margin between tooth and retainer, where increased plaque formation initiates the caries process, especially if the margin of the retainer is placed sub-gingivally, as well as periodontal irritation if not treated. Therefore, in this situation it is important to place the retainer's margins supra-gingivally whenever possible. Secondly, root caries may develop distant to the margin of the retainer.

3.5.4.1.2 Apical pathology/endodontic failure

The number of failures associated with apical pathology may reflect increased use of porcelain fused to alloy restorations, which require more tooth substance to be removed from the labial aspect (Karlsson, 1986). Marginal leakage, chemical irritation from cement media or occlusal trauma after bridge cementation, may add to the "insult" to the pulp and may lead to pulp death (Foster, 1990). This latter author stated that as the restorative treatment was performed by a large number of private general practioners the proper pre-operative pulp status was unknown. This may also be one of the major reasons behind the finding of 20.2% apical pathology in the current study. The possible reasons for the failure are complex as most of bridges were made by general practitioners with unknown pre-operative pulp status, and posts also used in 30.9% as bridge abutments. Other studies have reported that apical lesions occurred in 41-67% of teeth restored by posts (Turner, 1982; Fox *et al.*, 2004).

It will often be the case however that the dentist will have assumed the abutment to be vital at the time of cementation and the pulp condition is often difficult to precisely estimate, especially in the heavily restored tooth. Non vital pulp tissue of abutment teeth and peri-apical lesions are frequent findings in retrospective studies, possibly due to tooth reduction of abutment teeth. The incidence of necrotic pulps for abutment teeth has been reported as being 15% (Bergenholtz, 1991).

Bergenholtz and Nyman (1991) concluded that, even after years of service trauma from the preparation of the abutment teeth was the most likely cause of necrosis of the pulp. Following 10 years of observation Karlsson (1989) stated that necrosis of the pulp occurred in 10% of previously vital abutment teeth. To reduce trauma from the tooth preparation to the pulp tissue it has been suggested that preparation should be carried out using sharp instruments, using proper cutting speed with abundant cooling to reduce heat generation (Brannstrom, 1968; Walton *et al.*, 1986). In addition, the pulp tissues should be protected from chemical and thermal trauma (Baier and Glantz, 1978).

In Karlsson's study in 1986, periapical lesions were seen on radiograph in 10% (out of a total of 641 bridges) of the teeth. Other findings (Reuter and Brose, 1984) have reported lower results where seven out of 249 vital abutment teeth (2.8%) subsequently became clinically and or radiographically symptomatic after bridge cementation.

3.5.4.2 Mechanical failures

The longevity of fixed bridgework could be decreased by technical failures or in combination with biological reasons. The technical factors include fracture or dissolution of the luting cement (leading to loss of retention), fracture of the metal or other substructure of the bridge, fracture of aesthetic veneering material, fracture of the core, fracture of a post (diagnosed by use of radiography), and fracture of the abutment tooth.

The developments in materials and laboratory procedures have resulted in a significant reduction in bridge failures due to reasons such as fracture of veneering porcelain or fracture of metal substructure. However, fractures of post and core or fractures of abutment are still considered as significant causes of failure (Hammerle, 1994).

Nyman and Lindhe (1979) noted that non-vital abutment teeth were up to 3 times more prone to technical failure than vital teeth. One of the possible reasons for increased risk rates of non-vital teeth in comparison to vital teeth may be more mechanical loading of non-vital teeth due to loss of biofeedback (Glantz *et al.*, 1993) as well as the reduced tooth structure remaining after root canal treatment has been provided.

3.5.4.2.1 Loose retainers

The aim of the luting cement is to fill the space between the abutment and inner surface of retainer. Proper abutment preparation and luting cement selection help to keep the bridge in place during function. In order to reduce the risk of loss of retention, the general principles of tooth preparation should be followed. A carefully chosen preparation design, with the maximum surface area and minimum convergence angles gives the best of retention and resistance form for the bridgework (Jorgensen 1955). Jorgensen stated that the optimal taper of the preparation for maximum retention of the restoration should be around 5° from the vertical. However, tapering the preparation too little also may cause technical complications including difficulty in seating the restoration properly due to hydraulic resistance from the luting cement.

One of the frequent complications reported with fixed bridges is a loosened retainer (Goodacre *et al.*, 2003) and this had occurred in the current investigation in 20 bridges (11.9%) similar to results reported by Karlsson (1986) of a frequency between 5% and 12%.

Cheung *et al.*, (1990) reported that most of failures occur in fixed bridge and the highest incidence of loosening occurred in the upper anterior region.

Several studies have followed the frequency of loss of retention in fixed bridge over several years. Schwartz *et al.,* (1970) found that loss of retention was one of the most common complications after caries development, in fixed bridgework. These authors reported that 12.1% of failures were caused by loss of retention. This is in close agreement with the current retrospective service evaluation, where 11.9% of failures were due to loss of retention. The precise reasons behind these failures are unknown but these bridges were constructed by general dental practioners and it is possible that some of them were possibly less experienced and preparation guidelines may not have been fully followed. Maryniuk and Kaplan, (1986) attributed 50% of the failures in fixed bridgework to dentists and the materials used.

Nyman and Lindhe (1970) recorded that 3.3% of their investigated bridges showed loss of retention after 6.2 years in function, where Valderhaug (1991) reported 6.5% of loss of retention over observation period of 15 years. However, neither study recorded the reasons for the loss of retention.

In 2006, Curtis *et al.*, stated that 41% of patients were not aware that they had a loose bridge retainer until informed by their dentist. However, 82% of these patients who know they have a loose bridge reported no discomfort associated with awareness of a loose retainer and they did not feel it necessary to report these complications to their dentists to get treatment.

Loss of retention, if undiagnosed quickly, can often lead to serious complications. It can result, in a relatively short period of time, in the development of caries of the abutment tooth which is often a clinical sign helping to the diagnosis of loss of retention (Hammerle, 1994). In this situation however, it is often impossible to determine that the loss of retention is the cause or the effect of development of the carious lesion.

3.5.4.2.2 Post and core

The fracture of filling materials used to rebuild vital and non-vital abutment teeth often depends on the material been used. Where there is destruction of coronal tooth structure in a root filled tooth, the use of a post to achieve sufficient retention for a subsequent crown or fixed bridge is often helpful to restore these situations (Fox *et al.,* 2007). The ideal properties of post and cores include strength, corrosion resistance and proper marginal adaptation (Shillingburg, 1982). However, posts tend to fail by various means such as; debonding (where, if they deboned, recementation or remake may be possible) or fracture of the post and fracture of the root.

In the current retrospective service evaluation, loss of post retention associated with fixed bridgework was found to be 30.9% (52/168 bridges). As this study was based on patient records some of information was missing for parameters such as; type, length, fit of the post, amount of tooth structure remaining, and cervical collar of the crown. All these factors may influence the tooth and post retention, and some caution should be taken to generalise the results of this retrospective service evaluation. Post and core failure in fixed bridgework was noticed to be a great risk since the "gold standard" work by Roberts (1970) where 49 post crowns were used as major retainers. He stated that the failure rate of 4.35% be considered high and unacceptable and stressed that the maximum care must be taken if a post is to be used. It appears from this retrospective service evaluation study that general dental practitioners in this region of the UK were not following this advice. This would appear to be something that should be stressed in undergraduate and postgraduate teaching in the region in the future and the effect on failure rates then reassessed by a further service evaluation. Because of limited information being available from the case-notes, it was difficult to determine the accuracy of post failure and identify the parameters that contributed to the fixed bridge failures.

Post fracture often occurs in sites where there are high stress concentrations that would initiate cracks that would then propagate. This usually causes the post to fracture subgingivally, and its removal may be difficult, or in some situations, not possible.

Post failure is one of the most frequent causes of failures in fixed bridgework and means to increase the durability of root treated teeth such as; preservation of tooth structure, avoiding post insertion if possible and encircling the root with a metal collar in order to avoid root fracture, post fracture and loss of post retention should be used where a post is unavoidable (Assif *et al.*, 1989).

3.5.5 Limitations of the retrospective service evaluation

The limited information available from the case-notes means that caution should be observed when drawing conclusions from this study as data was missing from the case-notes to draw regarding different factors contributing to fixed bridge failures at Liverpool Dental Hospital.

A retrospective study looks back at events that already have taken place. In this form of study, the investigator collects data from past records, but does not follow-up patients as would be the case with a prospective study. Most sources of error in retrospective studies are due to confounding factors, which were not controlled for when the data was recorded, and therefore, for these reasons, retrospective investigations are often criticised. Retrospective studies have other disadvantages. One of these is that bias may affect the selection of controls (selection bias). Retrospective studies also need very large sample sizes to demonstrate rare outcomes.

Retrospective studies, though, do have their advantages, including the fact that they are often inexpensive and quicker to complete.

3.5.6. Conclusion

In conclusion, this retrospective service evaluation has shown that a variety of biological reasons i.e. Dental caries, apical pathology and endodontic failure as well as mechanical factors such as failures of post and core, and loss of retention contributed to the failure of fixed bridges referred to two honorary consultants at Liverpool Dental School. However, there was often data missing from the patients' case-notes that made it impossible for the investigator to identify the exact cause of failure.

One of the most frequent mechanical causes for failure was loss of retention. Given that this could lead to possible caries and eventual losses of a bridge abutment tooth an objective, reliable and reproducible method to identify early cement lute loss leading to retention failure of a fixed bridge would be of significant benefit. Several advantages of early diagnosis of retention loss could be gained such as; retention of a tooth that would otherwise be lost, conservative removal and recementation of the existing bridge with financial and biological benefits to the patient. The aim of this novel study is therefore to determine an objective, non-destructive, non-invasive, and reliable test of bridge stability.

The experimental work reported in chapters 4 and 5, outline the various stages in trying to devise such a test including pilot *in-vitro* work and the major laboratory-based experimental study.

4 THE *IN-VITRO* PILOT STUDIES

4.1 Introduction

Using information gained from the literature review (chapter 2), and the findings of the retrospective study (chapter 3), preliminary pilot-study work was planned. The information from the case notes confirmed that failure due to loss of retention of fixed bridgework was worth investigating. The principal aim was to assess the feasibility of testing mobility of bridgework *in vitro* two forms of models (one of conventional die-stone and one constructed from die stone but with the abutment teeth placed in a simulated periodontal ligament) with simulation of 100% bone support. Two all-metal fixed bridges (one cantilever and one fixed-fixed) were constructed and an Osstell Mentor apparatus used to assess mobility of these bridges using Resonance Frequency Analysis (RFA) with a Smartpeg fixed to the bridge with composite. The RFA was recorded from various directions to determine the viability and reproducibility of this method. Therefore, the aim of this chapter was to explore the utility of RFA to record fixed bridge stability *in-vitro* by investigating the viability of this method to differentiate between uncemented and cemented fixed bridges on two models. In addition, the effect of a periodontal-like model compared to all-stone models is considered.

4.2 Aims

The aims of the pilot study were to determine if an electromagnetic resonant frequency apparatus (Osstell Mentor, Integration Diagnostics AB, Gamlestadsvägen 3B, SE-415 02 Goteborg, Sweden) could prove capable of detecting movement of conventional fixed bridges on stone models. A number of variables required assessment.

4.3. Objectives of pilot study

1. To determine the viability of using Osstell Mentor with conventional fixed bridges.

2. To determine the viability of Osstell Mentor as being able to detect cemented and uncemented conventional bridges.

3. To inform the sample size necessary for the main experimental study.

4. To evaluate the ability to construct models with simulated periodontal ligaments ("periodontal" models).

5. To determine variables that may affect the Osstell readings, e.g. Smartpeg position, bridge design, simulated bone support, convergence angle of the preparations, "locking" of bridges by the stone of the models and the reproducibility of the method.

When this information was gained, including early results on viability, the main study, after discussion with a statistician to obtain a power calculation of the study, set the most pertinent variables for the main experimental work.

4.4 Materials and Methods

Before the commencing the main study a series of pilot studies were performed to inform the final method for the main experimental study. One operator (KO) performed tooth preparation to avoid inter-operator variability and to ensure that the required amount of tooth reduction had been carried out on all prepared teeth. Following tooth preparation on the master acrylic model, stone casts (working casts) were poured on which all-metal fixed bridges were constructed. . The complete details of the steps are discussed in the following sections in this chapter. Following information gained from the retrospective service evaluation a number of conventional fixed bridge designs were selected: conventional fixed-fixed bridges (CFFB) and conventional fixed cantilever bridges (CFCB) as shown in the flow chart shown in Figures 14 and 15. These bridges (in uncemented form as well as after cementation) were used in conjunction with stone models (2 CFCB, 4 CFFB) and "periodontal" models (1 CFCB, 2 CFFB).

4.4.1 Working cast with removable die

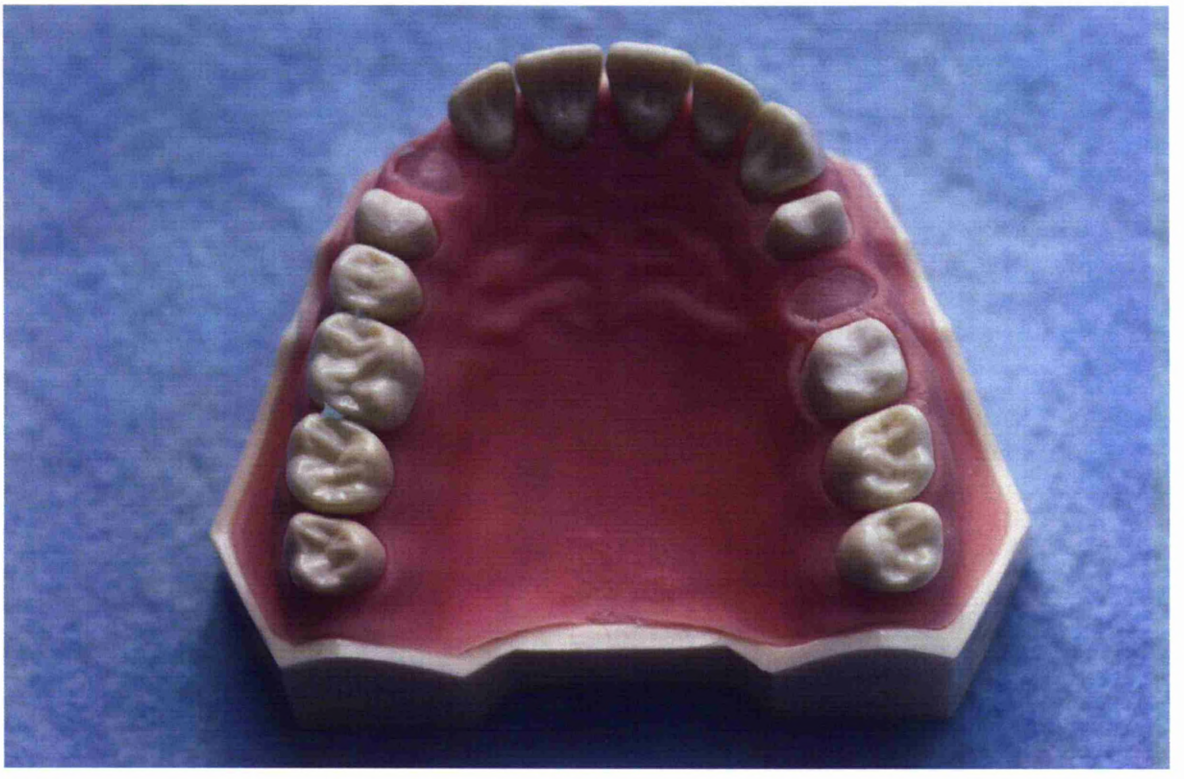
4.4.1.1 Impression making with polyvinyl-siloxane

This material is commonly called addition silicone, because of its setting reaction and is usually packed as two pastes. One paste contains silicone with terminal silane hydrogen groups and inert filler and the other paste is made of a silicone with terminal vinyl groups, catalyst and filler. When mixing equal amounts of the two materials, there is an addition of silicone hydrogen groups across the vinyl group with formation of no by-products. This results in a dimensionally stable set material (Shillingburg, 1997). Polyvinyl siloxane silicone material (Coltene Whaledent, Germany) is slightly affected by pouring delays, and by pouring a second model. Due to its dimensional stability the material was selected for this study. Surfactants incorporated into the material by the manufacturer make it more hydrophilic and easier to pour stone-based casts free of voids.

4.4.1.2 Putty index of prepared teeth

Two teeth were selected to be used as abutment teeth in the main study. The upper left first premolar and upper left first molar were prepared on a typodont model (Frasaco) (Figure 2) to receive a full metal coverage bridge incorporating minimal chamfer margins cervically and a clinically achievable preparation convergence.

Figure 2 Model with prepared teeth



4.4.1.3 Working Cast and Dies

When good impressions have been made it is important that they are handled properly to ensure that accurate working casts be made. There are requirements of proper casts such as; they must be bubble free especially at the finish line, all parts of the cast must be distortion free, and trimming of the cast must be performed to allow access to the wax pattern margins.

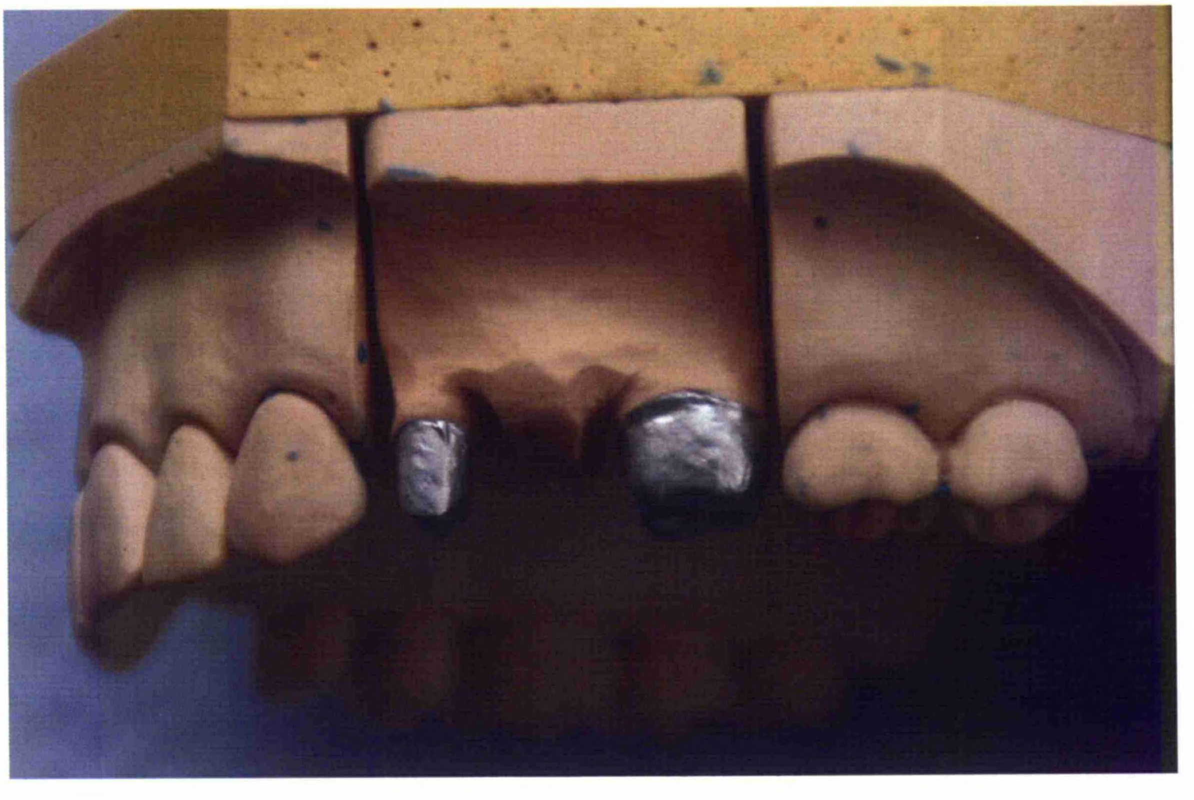
The die is a model of the individual prepared tooth on which the wax pattern margins are finished. There are two basic die systems; a working cast with a separate die (used in this study) as shown in Figure 3, and a working cast with a removable die. The separate die in addition to ease of fabrication, also keeps the relationship between abutments fixed and immovable but one of the disadvantages is that the wax pattern must be transferred from one to the other and this might cause distortion of the wax. The working cast with removable die is convenient to use and there is no need for copings to be removed from their dies, but one of disadvantages is the risk of introducing distortion into the pattern if the die is not reseated properly in the working cast.

The method of making the separate die, used in this study, started by construction of a stone working cast from a mould index. Dental stone was mixed with water and poured into the mould index. After setting, a separating medium was applied to the base surface of the cast and a Pindex machine used to drill two holes in relation to the long axis of the chosen abutment teeth (in this case the premolar and molar). Pins were placed to fit these holes and the rest of the mould then filled with stone material. This was left to set, and the working cast sectioned at the distal surface of canine the mesial surface of second molar tooth in order to produce a separate dies from the working cast as seen in Figure 3.

4.4.1.4 Impression Pouring

In this study, working casts with separate dies (Figure 3) were constructed (by KO) to make the bridge wax pattern for all the bridges. When the removable die system is used, it should be meet a few requirements (Cowell and Moore, 1965; Shillingburg 1997) such as the dies must return to their exact position and they must remain stable even when the cast is inverted.

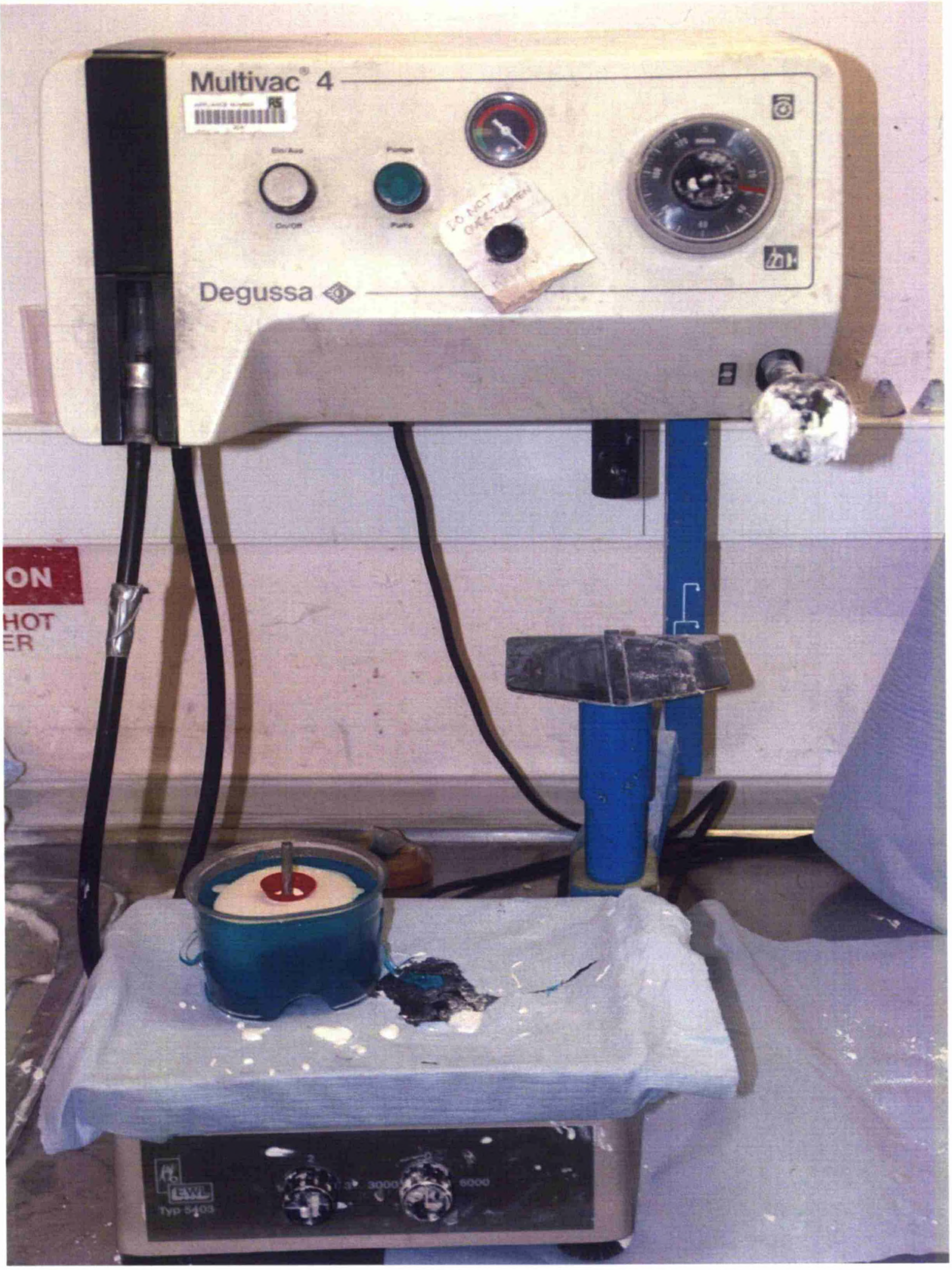
Figure 3 Working cast with separate die



The Wettability or surfactant (Debubblizer and wax pattern cleaner; American Dental Supply, USA) is formulated for investments to flow evenly over the wax pattern. It eliminates bubbles and reduces the surface tension for dental waxes. It is applied by spraying for 3-5 seconds over the surface of the working impression, which reduces the number of voids providing a cast free of voids.

Models were constructed by placing a measured amount of water (in ml) in a plastic mixing rubber bowl (Vac-U-Mixer, Whip Mix Corp, KY) (Figure 4) and a measured amount of die stone (70g) before mixing according to the manufacturer's instructions, with the water.

Figure 4 Vac-U-Mixers



The water/powder ratio affects the properties of the dental stone, including setting time, setting expansion, porosity and cast strength. Using a spatula for 10 seconds the water and stone were mixed until the stone was wet, a lid placed on the bowl, a vacuum tube attached and then vacuum mixed for 15 seconds. The surfactants were subsequently removed/ blown from the surface of impression without desiccating it.

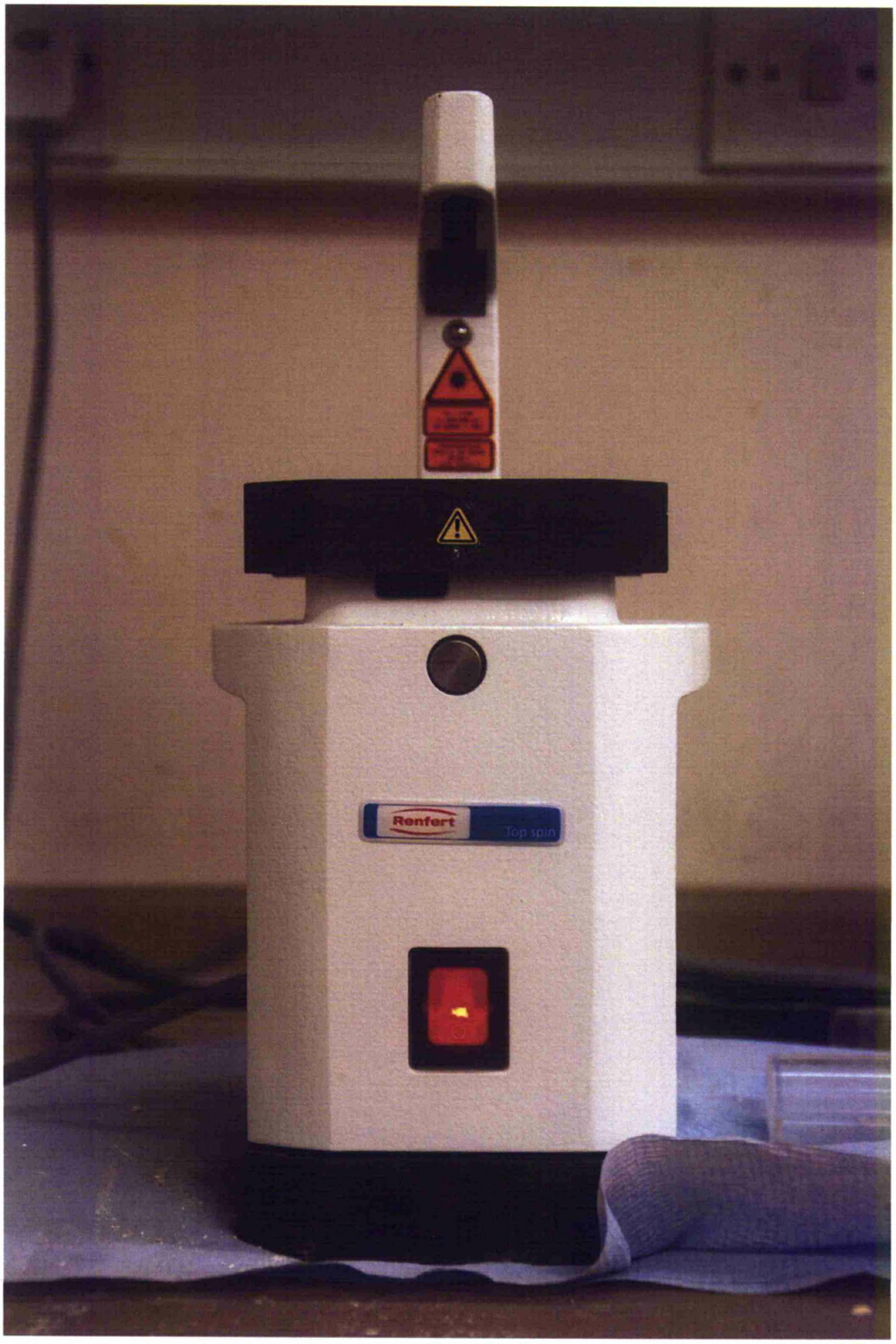
A small amount of stone was placed on the side of the impression above the preparation using a small instrument; and vibration applied until stone reached the bottom of the preparation. Stone was then added in small increments to fill the preparation then poured fill the entire impression to a height of about 2.5 cm over the preparation to allow bulk for an adequate die.

4.4.1.5 Pindex System

In the Pindex system (Coltene Whaledent GmbH. Raiffeisenstraße Langenau, Germany) (Figure 5) consisted of a reverse drill press which was used to create a master cast with dies that could be removed and replaced repeatedly in the same position. The machine produced parallel holes from the underside of a trimmed cast. The impression was poured as described above, allowing about 20 mm of stone. It was then allowed to set for one hour, removed from the impression and a model trimmer used to flatten the heels of the cast and the base of it trimmed. It then should sit flat on a tabletop to ensure that the pin holes drilled into it would be parallel. The model trimmer was then used to trim the stone to get about 15 mm thicknesses from the base to preparation finish line.

A pencil was used to mark the needed location of the pins on the occlusal surfaces of the prepared teeth (two pins for each die). The pencil marks were aligned with the illuminated dot from the light beam. Using both hands downward pressure was exerted on the cast and the drill assembly cut the pin holes. The base was poured in type II stone beginning in the area of pins. Whilst vibrating small increments of stone were added until they completely covered the pins. The cast was inverted and seated it slowly in the base former until the wax on the end of the pins contacted the bottom of the mould and was left to set completely. After removal of the wax the cast was trimmed on a model trimmer and the wax on the end of pins exposed.

Figure 5 The Pindex machine



The desired location of the saw cuts was marked on the buccal and lingual aspects of the cast. These cuts were to be performed distal to canine and mesial to the second molar. The saw was used to section the dies from the underside. The sectioning of the dies was completed from the occlusal parallel to the pins and all the way through the stone. After the dies were sectioned, they were trimmed and the finish lines marked with a red pencil. Then die hardener and spacer are applied to the dies. The cast now was ready for fabrication of the wax pattern.

4.4.1.6 Wax pattern

The wax pattern is the precursor of the finished cast restoration that will be placed on the prepared tooth/teeth. It was duplicated exactly through the lost wax investing and casting technique (all stages were performed by KO).

The first step in making a wax pattern after die lubrication is the fabrication of a thin coping or thimble through dipping the die into melted wax (yellow) in a container filled with molten wax. After allowing it to set, the excess at the margins was trimmed with the help of blade. Casting wax (Whip Mix Corporation, Kentucky; USA) was applied over the surface of the preparation on the dies, using a hot spatula until it was carved to resemble tooth surfaces as in Figure 6.

Figure 6 wax pattern of fixed–fixed bridge

A polyvinyl siloxane index (Figure 7, 8, 9) was fabricated to help standardise the shape of the waxed up bridge. It consisted of two separate parts, one part of the buccal/facial aspect of the prepared teeth and the second part for the lingual/palatal aspect of the same prepared teeth.

Figure 7 The silicone index placed from the buccal side of the working cast

Figure 8 The silicone index placed from the palatal side of working cast

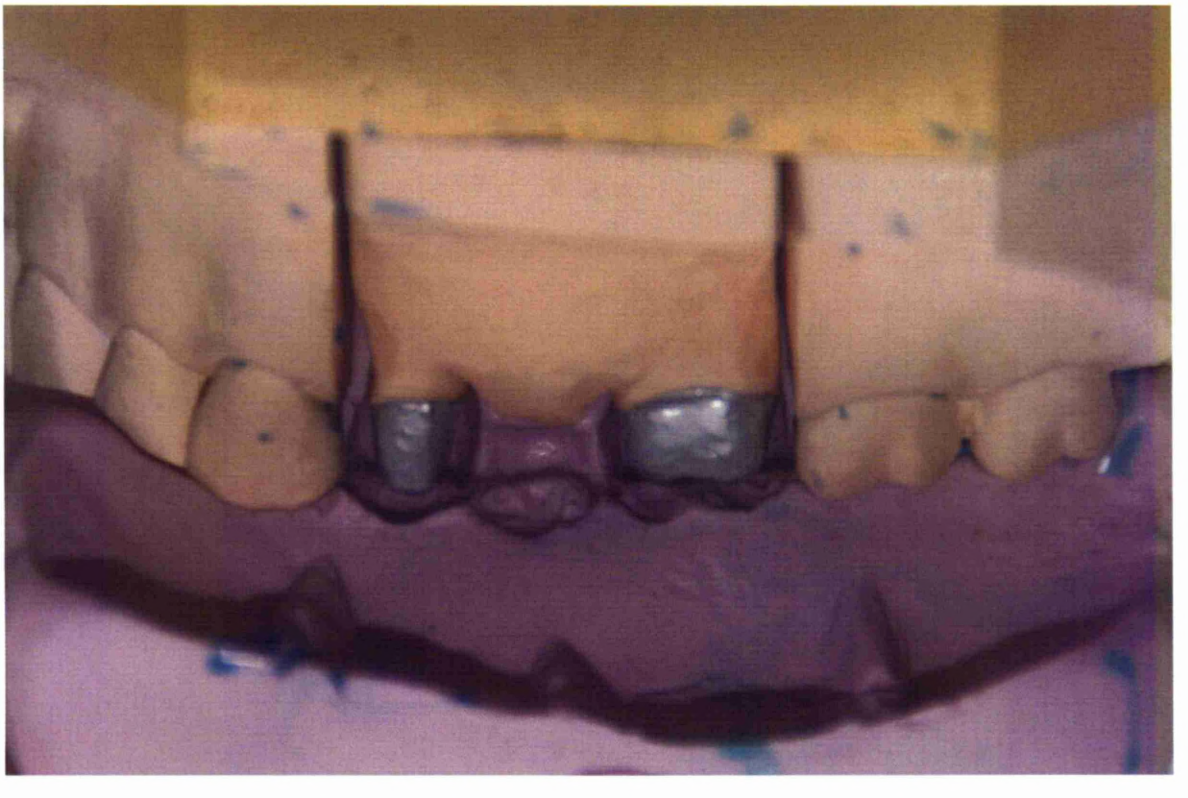


Figure 9 The two halves of the silicone index

4.4.1.7 Margin finish

After building up the entire bridge wax pattern, it was smoothed and checked to ensure that the red line on the margin was still distinct. Over-waxed margins, short margins, open margins and any roughness were corrected prior to finishing the wax-up procedure to produce a smooth surface that required a minimum of finishing.

4.4.1.8 Investing and casting

After fabrication of a wax pattern one operator (KO) performed the three steps to reach a completed casting; Investing, the burn-out procedure, and the casting procedure.

In this study the alloy used was nickel-chrome alloy that is used for ceramic bonding (Hera, Heraeus Kulzer, GmbH, Hanau, Germany) with a melting temperature of 1305-1400 °C. It consists of Ni 59.3%; Cr 24.0% and Mo 10.0%. Each bridge unit required approximately 1.5g of alloy. It has desirable properties such as low cost, strength and hardness, a high fusion temperature and few distortions during firing.

Disadvantages of these base metal alloys include excessive oxide formation, and, because of their hardness, difficulty in finishing and polishing. Nickel is also capable of eliciting an allergic reaction in some cases.

4.4.1.9 Investment material

The investment material must fulfil some important requirements, such as;

1. It must produce sharp details/shape form of the wax pattern
2. It must be hard enough and have proper strength to withstand the high temperature during burnout and casting procedure.
3. It should have a matched property of expansion to compensate for shrinkage of the alloy.

4.4.1.10 Spruing

A sprue with reservoir (Skillbond Direct Ltd Dudley House, High Wycombe, Buckinghamshire, UK) was attached (by KO) to each retainer and pontic wax pattern. The main sprue was attached to the crucible forma (a conical rubber base). When the crucible former was removed from the ring after the investment had hardened, it left a funnel shape that allowed entrance of the molten metal. The sprue former was attached to the greatest bulk of the wax pattern. It was attached at an angle to allow the incoming alloy to flow freely to all parts of the mould cavity. Wettability material was sprayed on the waxed bridge, and allowed to set prior to investing.

4.4.1.11 Investing procedure

For each specimen a plastic casting ring was placed on the crucible former which allowed the setting expansion of investment material. The plastic ring was removed before the invested pattern was placed into the oven so that it allowed easier escape of gases from the mould cavity during casting. Air bubbles in the investing material may result in nodules on the casting, and because of this vacuum mixing was used to produce the best casting.

The manufacturer's powder/water ratio was mixed at room-temperature. A debubblising agent (Debubblizer and wax pattern cleaner, American Dental Supply, Inc, USA) was painted onto the wax patterns before they were invested.

70 g of phosphate bonded material (Heravest Speed, Hearaeus Kulzer, Germany) was added to the 30ml water and mixed with a spatula until all the investment had become wet. This was then vacuum mixed (Vac-U-machine, Figure 4) for 15 seconds. The investment was poured down one side of the ring under constant vibration, and gradually filled from the bottom up wards (to remove the air bubbles). Material was added until the ring was full and then left to set at room temperature.

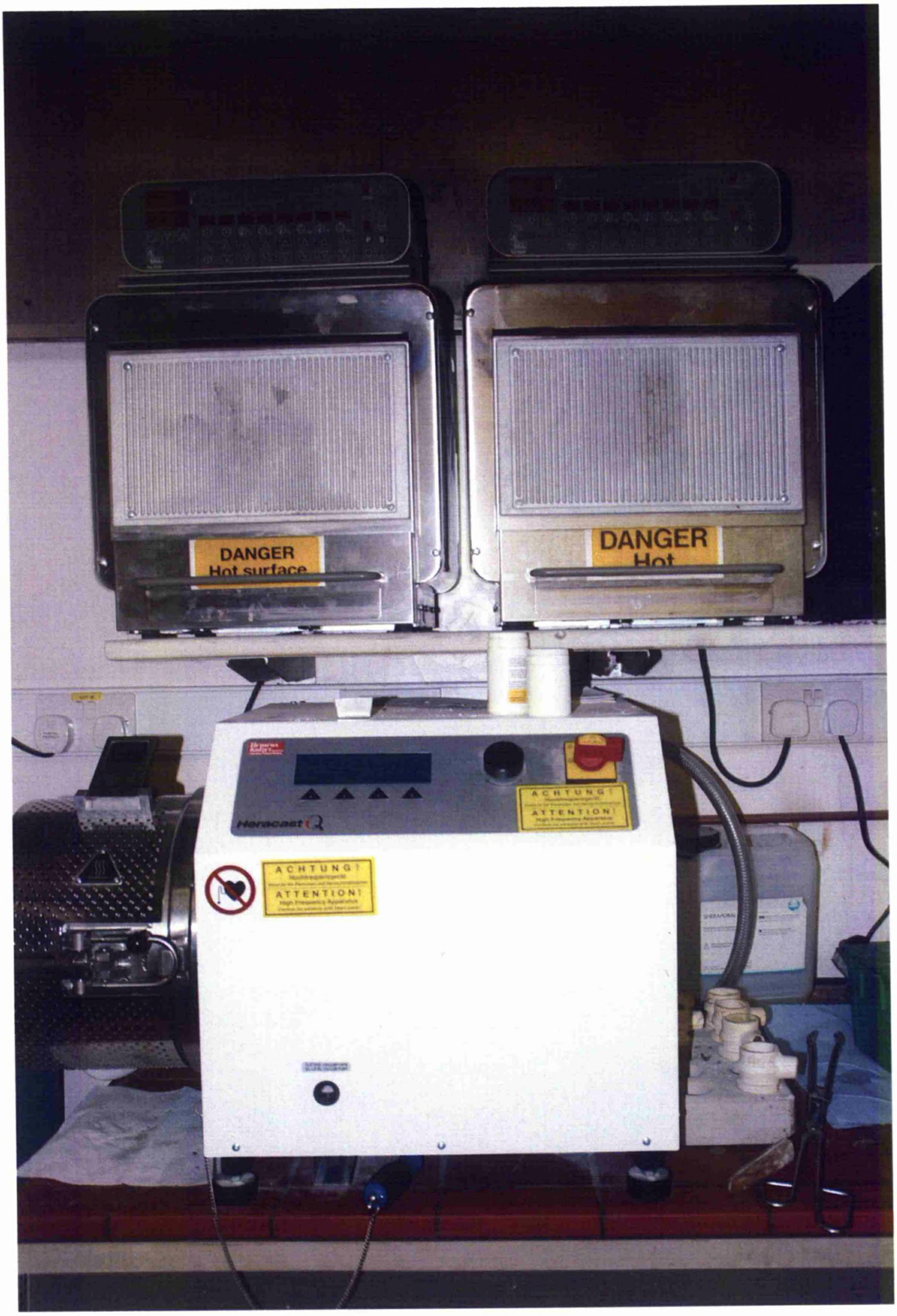
4.4.1.12 Burnout procedure

This is a process where the mould is prepared for molten alloy and at the same time thermal expansions occurs. The crucible former was removed carefully. The casting ring was placed with the crater down into the oven (Figure 10) and heated slowly to the casting temperature. The wax patterns were burned out at temperature of 980 °C.

4.4.1.13 Casting procedure

The casting alloy was placed in the crucible of the casting machine with enough bulk of metal alloy to fill the mould cavity, the sprue, and part of crucible former to ensure sharp, complete details in the casting (~1.5g for each retainer or pontic). The casting machine (Combilabor CL195, Heraeus Kulzer, Germany) (Figure 10) was switched on to melt the alloy automatically as the temperature rises with time. The ring was placed in the bracket on the casting machine and heating continued until the alloy "balled up". At this stage the casting ring was removed from the oven with the help of casting tongs and the ring placed in a cradle. The platform on which the crucible former rests was placed against the ring ensuring a snug fit. The switch was operated to turn the cradle with the crucible former, to allow the molten alloy to enter the mould cavity automatically. Following this, the ring was removed from the machine and left to cool at room temperature.

Figure 10 The Oven (top) and the casting machine (below)



The investment was removed by hand with the help of instruments. The resultant oxide layer and any investment material on the casting were removed by sandblasting of all surfaces with a fine air-propelled abrasive (100μm aluminium oxide using a sandblasting machine, Bifa, Germany) (Figure 12).

4.4.1.14 Finishing and polishing of casting

The casting that was retrieved from the investment was rough with many irregularities that required smoothing and polishing. Preliminary finishing, try-in and adjustment were performed before polishing. A cut-off disc was used to remove the sprue after air abrasion of the casting. Any internal/external small nodules were removed from the casting before try-in on the working cast and any areas of premature binding adjusted and the casting reseated until a proper fit was achieved (Figure 11). Because of the greater hardness of the base metals, binding areas were identified using disclosing sprays used until the casting could be seated and removed from the die with gentle finger pressure. All castings were finally sandblasted before they were then used for BSQ testing.

Figure 11 Working cast with metal fixed bridge on perio model

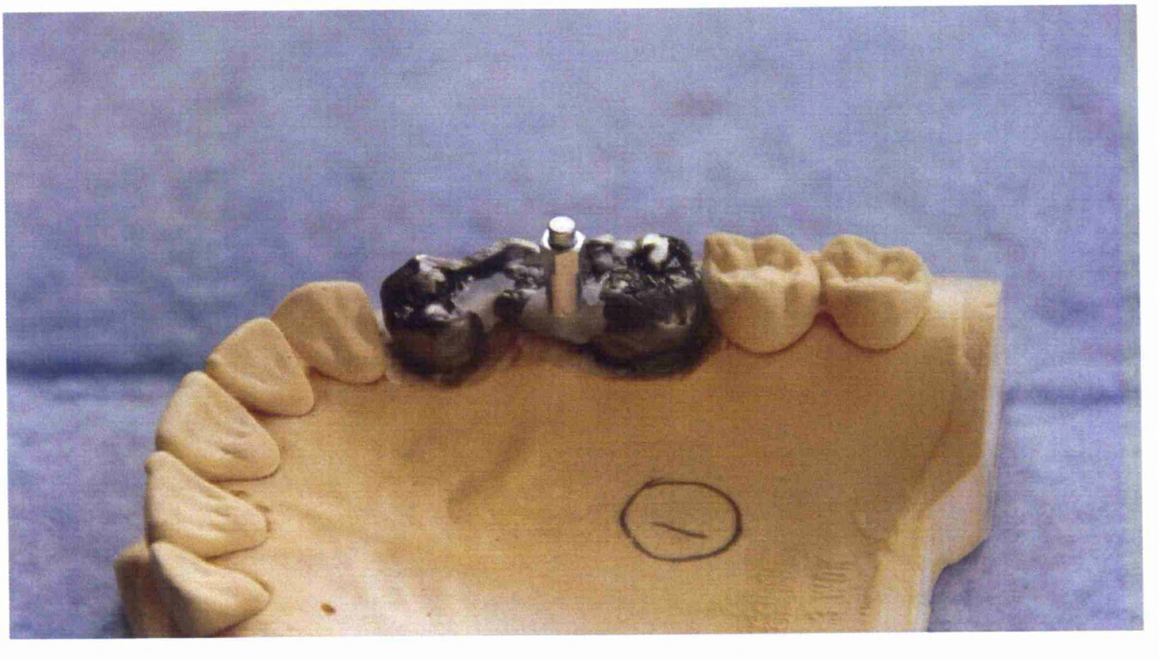


Figure 12 Sandblasting machine

The stone model and fitted fixed bridge was placed on a dental surveyor (model 1451 Nesor Products Ltd, UK). In order to prevent movement of the model during recording of measurements, it was placed and fixed on the surveyor table with the help of three stabilising screws. The position of the table was held horizontally during the recording of all measurements.

4.4.2 Working cast with a periodontal membrane (Periodontal models)

As the RFA equipment assesses movement it was considered that a simulated periodontal ligament would more closely resemble the clinical situation. The aim of this aspect of the pilot study was to construct models with periodontal ligament like material around the carved stone abutment teeth in order to more closely resemble natural tooth movement within the alveolus. Prepared stone teeth (premolar and molar abutments) were carved with the help of a double sided disc to resemble natural tooth root structure with either two (premolar) or three roots (molar) as shown in Figures 24 and 25. The stone tooth analogue was then held in forceps above the line approximating to the CEJ and the roots were dipped into elastomeric impression material (polyvinyl siloxane) to gain one coat and allowed to set. The material is elastic in nature and dimensionally stable in an even thickness (Reisbick and Matyas 1975). These carved stone teeth were repositioned into the mould impression and dental stone (supra-hard, ISO type IV, Kerr, Italy) was poured into the mould and left to set. The periodontal working cast was recovered, cleaned and adjusted.

4.5 Resonant frequency analysis (RFA)

RFA offers a clinical, non-invasive measure of stability and presumed osseointegration of dental implants (Meredith *et al.,* 1998) and an objective method to evaluate *in-vitro* and *in-vivo* studies (Meredith *et al.,* 1996, 1998). A transducer is connected to the implant or abutment, the beam is excited over a range of frequencies and resonance frequency (RF) is measured by the use of a frequency response analyser (Osstell, Integration Diagnostics AB, Gothenburg, Sweden) (Figure 13) which is connected to a computer and run with software.

Figure 13 Osstell Mentor with probe

4.6. Study design

This method, although designed to assess implant stability, is actually a non-invasive and reproducible means of measuring movement. If it is considered likely that a failing bridge moves more than an intact bridge, resonance frequency analysis may allow this to be detected.

Resonance frequency measurements were calibrated by using a calibration block that been supplied by the manufacturer. Calibration was performed after each set of ISQ readings (uncemented bridges ISQ values, cemented ISQ values) in order to ensure that the Osstell Mentor gave the same readings all times to enable more consistent measurements to be obtained.

The values were transformed, via the software, to Implant Stability Quotient (ISQ) units, which are presently used to describe implant stability with the RFA technique. A value between 1 and 100 is obtained, where 1 is the lowest and 100 the highest measure of stability. Less information has been reported regarding the influence of the transducer position.

According to Meredith *et al.,* (1996) the response of the transducer is directional and different ISQ values are to be obtained in different directions.

For each retainer of the fixed bridges in the pilot study, a Smartpeg was fixed temporarily with the help of composite resin (Coltene/Whaledent Ltd, Kendal House, Burgess Hill, West Sussex, UK) at the rigid connector site (embrasure area) of the palatal metal surface of the bridge. The Smartpeg should be fixed at a certain length as been recommended by the manufacture to give accurate and consistent measurements. This was ensured by the principal investigator placing the Smartpeg at the embrasure area and completely covering the threaded portion with composite resin before curing. The length of the Smartpeg must be fixed at the same length at all times to prevent the Smartpeg resonating at different frequencies and affecting the Osstell readings.

Readings were recorded using the Osstell monitor probe from a distance of 1-3 mm. Measurements were taken from the surfaces of the Smartpeg that were facing Buccally, Occusally, Palatally, Mesially and Distally in order to investigate the viability of testing the null hypothesis that there is no difference in Osstell readings obtained from different surfaces of the tested bridge. Ten measurements were recorded each time for each transducer position, for each bridge. All the ISQ values were transferred to an Excel2007 (Microsoft) spreadsheet where initial data sorting took place.

Statistical analysis was subsequently carried out using MINITAB 15.

4.7 Results of pilot studies

In this pilot *in-vitro* study, all fixed bridge work had to be stable, to finger pressure, in position on stone models before the ISQ was measured.

The highest mean stability (ISQ 78) value was recorded on a cemented fixed-fixed bridge. The lowest mean stability (ISQ 59) value was obtained from uncemented fixed-fixed bridge on premolar as shown in Table 9.

The fixed bridges used in this study were split into two groups according to their mode of fixation-uncemented and cemented fixed bridges, and into two groups according to the number and position of abutments, cantilever and fixed-fixed bridges as shown in Table

4.7.1 Uncemented fixed bridge

There were six uncemented bridges on stone models, four of them were fixed-fixed bridges and two were cantilever bridges as shown in Table 8.

The mean (SD) ISQ value using RF analysers were recorded for six uncemented fixed bridges on stone models (2 cantilever and 4 fixed-fixed bridges). Five of these bridges were cemented on stone models (1 cantilever, 4 fixed-fixed) and other one cantilever bridge on a reduced bone support periodontal model. The ISQ reading were taken as shown in Table 9. It also shows the mean ISQ values for 3 uncemented fixed bridges (1 cantilever, 2 fixed-fixed bridges) on periodontal models.

Table 8 Mean and SD ISQ values for cantilever and fixed bridges on stone models A, B, C and D and periodontal model (buccal surface records only reported)

	Mean (S.D.)ISQ values for each cantilever bridge	Mean (SD) ISQ values for each fixed-fixed bridge
Uncemented bridges on stone models	75 (SD=3.87) 59 (SD=6.91)	67 (SD=0.33) 59 (SD=1.03) 78 (SD=15.37) 71 (SD=0.5)
Uncemented periodontal model	50 (SD=5.66)	68 (SD=0) 55 (SD=0.5)
Cemented bridges on stone models	70 (SD=12.26)	60 (SD=0.73) 82 (SD=0.66) 78 (SD=3.33) 81 (SD=8.33)

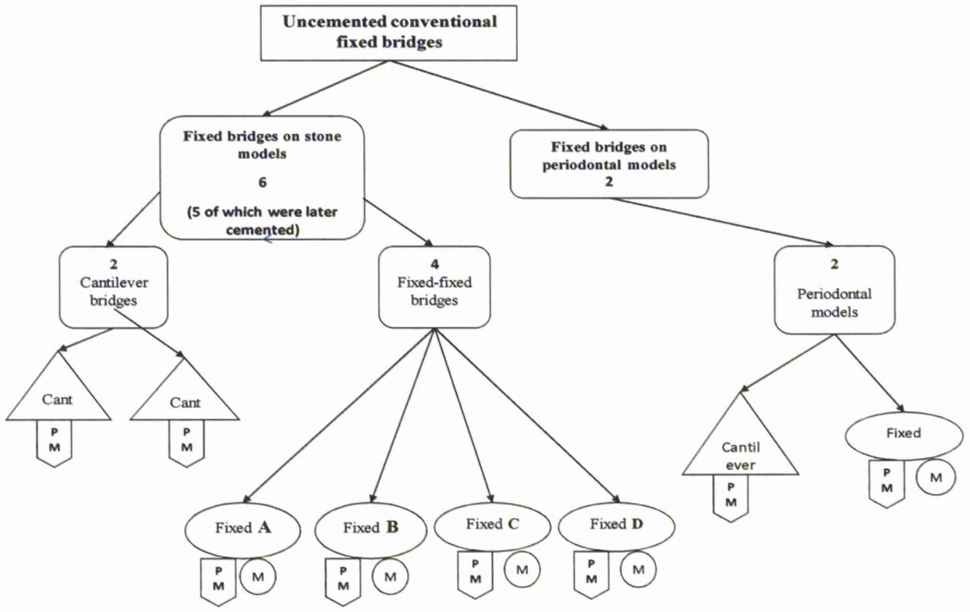
In this study, the highest ISQ value of the uncemented fixed-fixed bridges was 78, while for the uncemented cantilever bridge was 75. An interesting finding is the higher average of the ISQ value for the uncemented cantilever bridge.

Before fixed bridge cementation, all bridges had to be considered to be stable on the stone models to digital (finger) pressure. The ISQ value varied in 59 – 78 range, there were no major differences noted when looking at the direction of recording of ISQs on any of the models.

Table 9 Uncemented fixed-fixed (only two fixed bridges were made) on stone models A or B versus Periodontal model P: direction from which measurements taken

	Stone model A		**Stone model B**		**Periodontal model P**	
	Mean	SD	Mean	SD	Mean	SD
Buccal surface	69	0.00	82	1.95	55	0.51
Occlusal surface	67	9.90	82	3.19	57	2.35
Palatal surface	69	0.52	84	0.00	56	0.00
Mesial surface	69	2.60	79	3.14	60	2.69
Distal surface	70	2.90	76	0.96	57	2.36

Figure 14 Flow chart for uncemented and cemented fixed bridges both on stone and periodontal models

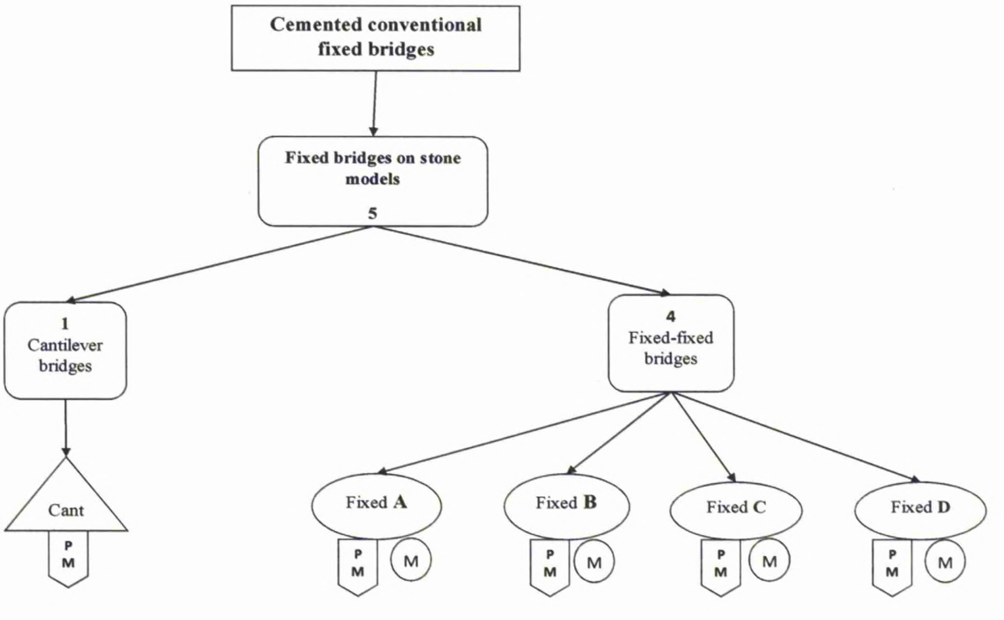


PM= premolar; M = molar

4.7.2 Cemented fixed bridges on stone models

All fixed bridges had to be stable to digital pressure (if uncemented) or cemented (using zinc phosphate cement) on the stone models before ISQ was measured. There were four metal fixed bridges cemented on four stone models. These were all made by the same investigator and constructed from the same materials as shown in Table 8. ISQ values of stone model A was compared to stone model B, stone model A compared to stone model C etc. Once again it was observed that the direction of recording of ISQs did not have a major influence on the obtained results.

Figure 15 Flow chart for cemented fixed bridges both on stone models



The uncemented fixed bridges group with lowest ISQ value showed the least bridge stability and the cemented fixed-fixed bridge group, with the highest ISQ value, showed the greatest in bridge stability.

4.7.3 Periodontal membrane model

There were three stone models with Polyvinyl-siloxane placed over the "roots" of the abutments that then had uncemented bridges tested (two fixed-fixed bridges and one cantilever bridge). Mean ISQ values for the periodontal model were 50 (SD=5.66) for the uncemented cantilever bridge and ISQ values of 55 (SD=0.5) and 68 (SD=0) for the uncemented fixed-fixed bridges.

4.7.4 Reproducibility

To assess the reproducibility of the method two investigators independently recorded values from the same models, using the same method and the results assessed using ANOVA (Table 10). First two models (A and B) were chosen by second investigator for comparisons.

Table 10 Comparison of results obtained for uncemented fixed bridges on stone models

	Stone model A, Investigator 1vs Investigator 2		Stone model B, Investigator 1vs Investigator 2	
	Mean	SD	Mean	SD
Buccal surface	69	0.31	83	0.00
Occlusal surface	70	2.84	84	2.46
Palatal surface	69	1.23	84	0.00
Mesial surface	70	0.67	70	4.34
Distal surface	70	2.89	79	8.77

4.8 Statistical Analysis of pilot study

The aim of this pilot study was to determine whether;

1. The RFA method using Osstell equipment is able to measure fixed bridge stability *in-vitro.*

2. The RFA method is able to detect a difference in bridge stability between uncemented and cemented fixed bridges.

Descriptive statistics including mean values and standard deviations were used to describe changes in bridge stability.

4.8.1 Uncemented fixed bridges

In this pilot study there were no statistically significant differences ($P>0.05$) between the different stone models A, B, C and D. However, there was a statistically significant difference ($P<0.05$) between the uncemented fixed bridge on stone model B and the uncemented periodontal model P as demonstrated in Table 9.

The uncemented cantilever bridge on stone model B was tested against periodontal model P and found that there was a statistically significant difference ($P<0.05$) between them.

ISQ readings taken from the buccal surface were reproducible in most uncemented stone models and repeated measures showed there were no statistically significant differences ($P>0.05$) recorded between uncemented stone model A, B, C and D.

4.8.2 Cemented fixed bridges

Uncemented fixed bridges on different stone models were cemented using zinc phosphate cement onto the stone model and the cement was allowed to set for 30 minutes.

ISQ readings taking after cementation procedure showed that there were no statistically significant differences ($P>0.05$) for most recordings taken from different surfaces. ISQ readings of different buccal surfaces of cemented stone models showed no statistically significant differences ($P>0.05$) and they were repeatable on all stone models.

4.8.3 Uncemented versus cemented stone models

After ISQ readings were recorded from uncemented stone models, the bridges were cemented using zinc phosphate cement and ISQ values were recorded.

There were three uncemented stone models having fixed bridges compared to three cemented stone models. ISQ readings showed that there were statistically significant differences ($P<0.05$) between the uncemented and cemented bridges.

4.8.4 Periodontal model P

The uncemented cantilever bridges on stone model B were tested against uncemented bridges on periodontal models P and it was noted that there were statistically significant differences ($P<0.05$).

Uncemented fixed-fixed bridges (new model A and B were made) were tested against periodontal model P. It was noted that there were statistically significant differences ($P<0.05$) between both stone models and periodontal model P as was the case in Table 9.

4.9 Discussion of pilot studies

The RFA method with the Osstell (Integration Diagnostics, Sweden) equipment has been claimed to be useful for;

1. Monitoring implant osseointegration during the healing phase (Meredith 1998)
2. Helping the clinician decide on an individual basis when to load an implant (Glauser *et al.,* 2001).

Use of Osstell resonance frequency analysis equipment to detect differences between bridges on different models was undertaken. A number of variables were assessed and the pilot results demonstrated the viability and some limitations of the technique.

4.9.1 Resonance Frequency Analysis method

The assumption is that implants are supposed to increase their stability with time. Also, that implants that achieve a high primary stability might be loaded earlier after their placement (Meredith *et al.,* 1998).

In this pilot *in-vitro* study the use of RFA method with the Osstell equipment appears to be useful to detect the fixed bridge mobility on a stone model before and after cementation.

The process of construction of stone models that may have inadvertently been affected by porosity or setting expansion may have resulted in non passive fitting of the metal bridge on the stone models. In one stone model the metal bridge became 'locked' by the stone and could not move independently, resulting in a high Osstell reading.

The use of RFA with a Smartpeg was fixed temporarily with resin composite. The Smartpeg must be fixed at certain length (recommended by the manufacturer) to produce consistent measurements from the Osstell apparatus, and this should make it possible to repeat measurements over time, so that any changes in fixed bridge stability could be monitored and mobile bridges can be detected before catastrophic failure with simpler retreatment.

4.9.2 Uncemented bridges on stone model

Within the pilot work there were two types of models used one was type was constructed entirely from dental stone and the other had a simulated periodontal ligament around the tooth analogues (Periodontal models (P).

The results showed that the ISQ readings measured using the Osstell equipment are not significantly influenced by the direction the probe is used. The literature suggested that the recommended direction to record ISQ was from the buccal surface, due to easy accessibility (Meredith *et al.*, 1997). In the present study ten readings were recorded from each surface of the Smartpeg, the mean of these values was calculated to give the reading obtained from that surface.

On use of one-way ANOVA analysis, it was observed that there were no statistically significant differences in Osstell values obtained from all directions (buccal, palatal, occlusal, mesial and distal) on uncemented fixed-fixed bridges on stone models.

There was, however, a statistically significant difference resulted when uncemented fixed-fixed bridges on stone model (Table 9) was compared to uncemented fixed-fixed bridges on periodontal model P. This result would suggest that the decrease in the ISQ value in the case of periodontal model P was attributable to an increase in tooth movement due to the periodontal membrane-like material siloxane around the abutment on periodontal model. Conversely, there were no such changes in ISQ readings *in-vitro* between fixed bridges on stone models due, probably to the rigidity of the stone material around the abutment.

An interesting finding in the present study was that of a higher ISQ value obtained for an uncemented cantilever bridge in a comparison to an uncemented fixed-fixed bridge. The mechanism behind this increased value is probably related to an increase in the mechanical factors of retention of the particular cantilever bridge in this study. It is likely that the parallel surfaces of the abutment and single path of insertion may have increased the retention and resistance form of this bridge. There is also less "length" for any leverage effects to influence the mobility of the bridge during testing.

4.9.3 Cemented bridges on stone models

The fixed bridges used in this pilot study were cemented with the use of zinc phosphate cement over the stone models that had been used to measure the ISQ value for uncemented fixed bridges. The cemented bridges were allowed 24 to set for 24h, when the Osstell readings were then recorded (on both stone and periodontal models). The selection of this cement was based on its physical properties and its long term use as permanent cement for bridge work. However, this cement may desiccate if left too long at room temperature. This (dehydration) is my cause the cement to break down and fracture leading to subsequent loss of retention of the fixed bridges which would affect the obtained ISQs.

It was observed that there were no statistically significant differences ($P>0.05$) between different cemented fixed bridges on different stone models. It was also noted that ISQ readings taken from the buccal direction were not significantly different from each other in all uncemented fixed-fixed bridges on stone models. This might be considered an important result as it suggests that this is a reliable direction to use for assessment and could subsequently be reliably used as the only direction from which to measure ISQs (rather than e.g. Occlusal or Palatal surfaces).

4.9.4 Periodontal models

The ISQ values of the present study calculated from the different bridge surfaces for each periodontal model were compared to results from uncemented cantilever and fixed bridges on stone models There were positive statistically significant differences ($P<0.05$) in ISQ readings between bridges over stone models and bridge on the periodontal models. This finding is not unexpected in view of high stiffness of stone models compared to resiliency of the periodontal membrane *in-vitro* pilot study model. It is well known that periodontal ligament acts as a cushion to absorb the stress and allow a slight tooth movement as a protective measure to prevent tooth fracture. The thickness of the polyvinyl-siloxane was measured with the help of callipers after the carved root of the stone analogue tooth was dipped into the elastomeric material once to obtain the required thickness. However, this thickness was not very uniform on all root surfaces, and the slight variability in this may have affected the ISQs, even going so far as to be deficient with resultant locking of the tooth into the stone. However, the relatively lower results that were obtained on the periodontal models tend to suggest that this 'locking', although possible, did not occur.

A decrease in the ISQ value to 50 for an uncemented cantilever bridge on the periodontal model P was noticed in comparison to Osstell values of 75 and 59 of the same design of bridge on stone models. It is likely that the drop in the ISQ value resulted from the use of the simulated periodontal membrane around the abutment in periodontal model P. This allows the abutment to move to a certain degree along with the bridge cemented to it. However, Meredith *et al.*, (1996) described a non-invasive method to assess implant stability and to monitor bone formation around the dental implant *in-vitro* and *in-vivo*. Bone anchored dental implants are being used widely on daily basis dental practice.

It is now well known that a direct union between the implant surface and the surrounding living bone is termed osseointegration (Meredith *et al.*, 1996). The technique measures the resonance frequency of a small transducer attached to an implant fixture or abutment which is directly attached to bone surface (no periodontal membrane as in tooth *in-vivo*).

A number of factors influence the stability of an implant. These include the amount of bone surrounding the implant and its quality and quantity, the length and type of implant used.

Johansson and Albrektsson (1991) conducted a study and they showed that bone formation at the implant interface (no periodontal membrane) during healing process resulted in an increase in implant stability. This would explain the increase in resonance frequencies observed. It has been shown *in-vitro* (Meredith *et al.*, 1996) that the actual ISQ value is related to the stiffness of the implant fixture in the surrounded tissues. However, in the present study the result showed that using periodontal membrane would decrease the ISQ value and it is related to the softness of the periodontal membrane around the abutment.

4.9.5 Reproducibility

Repeatability of the measurements in the present study was found by assessing inter-examiner results using one-way ANOVA analysis for ISQ readings obtained from stone models.

The repeatability between two different blind intra-examiner results was tested using the ISQ values recorded for uncemented fixed bridges on stone models from different directions. It has been showed that there were no significant differences in values recorded from the same directions. It is likely that this result because of fixed bridges were identically made on the same duplicated stone model.

No defined "cut-off" ISQ value has been validated through documented studies to determine the threshold value that discriminates between a mobile and a stable implant or fixed bridge. Nedir *et al.,* (2004) conducted a study to determine the cut-off ISQ value, and they concluded that ISQ <47 could be confirmed as clinically mobile implant. In this study similarly ISQ< 47 used as a cut-off value to consider a mobile fixed bridge.

The ISQ value provided by the Osstell equipment could not serve as a reliable diagnostic mean to identify a mobile implant with accuracy. In contrast, the Osstell was found to be a reliable diagnostic tool capable of identifying the stable implants with certainty (Nedir *et al.*, 2004) and all stable implants could be identified without error.

Clinically, the ISQ>49 should be reliably suggested that implants are Osseointegrated and these require minimal follow-up. On the other hand, less stable implants with ISQ<49 might need more follow-up and they are at higher risk (Glauser *et al.*, 2004). Implant stability above 65 ISQ should be regarded as optimal, and a value below 45 ISQ or a decrease ISQ value should be looked as an early warning sign. This does not imply that these same results are transferrable to cemented fixed bridges.

With respect to the bridgework results, *in-vitro*, in this pilot study the least stable cemented fixed-fixed bridge recorded an ISQ of 60 (SD=0.73) (Table 8). At this stage it could be fair to state that an ISQ of <60 is indicative of cement failure on stone models. However, the total number of evaluated fixed bridges in the pilot study is too limited to firmly draw this conclusion. Nevertheless, the results should be taken as indicative until a large sample size and better documented studies are produced.

This pilot study also demonstrates that the technique is highly reproducible between two investigators with only one set of measurements (recorded from the palatal surface) on one model being statistically significant (p<0.008) over ten parameters (Table 10).

4.10 Limitations of pilot study

The total numbers of evaluated bridges on stone models and on periodontal models were too few to draw a definite conclusion. A larger sample size to obtain a significant statistical power is to be carried out on the next, main, study on which will be refined on the basis of the pilot study results.

Only cantilever and fixed bridges were used in this pilot study. As a result of this no clear idea of how other bridge designs would respond to RFA equipment, this could be investigated in future studies when more definitive results are gained for fixed-fixed designs.

All fixed-fixed bridges were constructed in the posterior region using the first premolar and first molar as abutments. Fixed-fixed bridges are used commonly in the posterior site as it is considered that they give the maximum retention and are a successful design of bridge. This is due to the bulk of tooth surface and large clinical tooth length that increases the primary retention factors by virtue of the large surface area available. However, failure of one or both of these abutments could dangerous and costly to the patient and dentist. Roberts (1970) noted that failure tended to occur at the minor retainer and so, in the case of fixed-fixed bridges retained by the first molar and first premolar, we would expect that cement failure would occur on the premolar abutment. The outcomes of this pilot study informed the choice of using a metal framework fixed-fixed bridge to investigate differences in ISQs readings.

The positioning of a Smartpeg on the metal bridge by composite resin at the embrasure area was considered as one of the limitations of this study. The limitation arises because of the difficulty of fixing the Smartpeg reproducibly in the same position and at the same length on all the models throughout the study. However, the principle investigator was aware about this issue and ensured the repeatability could be achieved. Alternative techniques such as soldering the Smartpeg to the metal framework or screwing it into a pre-taped hole in the metal framework were considered but were not transferable to the clinical situation.

As this study was investigating bridges not implants it was proposed that the term Bridge Stability Quotient (BSQ) rather than Implant Stability Quotient (ISQ) is used in the main experimental work.

4.11 Conclusions of the pilot studies

This pilot study showed that Osstell instrument may be a viable technique for measuring bridge stability *in-vitro*.

Osstell instrument readings (BSQ) were not different when recording from different directions As a result, a buccal position of the Osstell probe was chosen for BSQ readings.

Within the limitations of this pilot *in-vitro* study, it can be concluded that the inter and intra-examiner repeatability of the Osstell measurements was satisfactory.

5 THE MAIN *IN-VITRO* STUDY

5.1 Introduction

In chapter 4, different fixed bridge designs and two types of models were used, RFA value data was collected, investigated and analysed. This chapter outlines use of the findings from the pilot studies to refine the methods of recording RFA values on periodontal models (simulating 100% and 50% bone support) from the buccal surface direction using acrylic abutment analogue teeth, with material to simulate periodontal ligament on their root surfaces, with sufficient sample size following power calculation (in conjunction with statistical advice). The use of RFA to evaluate fixed bridge stability *in-vitro* is investigated and two groups (control and test) assessed on the basis of controlled, blind and stratified randomisation. All convergence angles were standardised on all models. The data were collected from all models, and analysed, including use of Receiver Operating Characteristics (ROC) curve on the 100% and 50% bone support models to determine the validity of the measurements of the method. The sensitivity and specificity were assessed from ROC curve and the cut-off point calculated. Above this the fixed bridge is considered stable and below this it could be considered unstable or at risk. Calibration of the Osstell apparatus was performed throughout to ensure consistency of the measurements. The outcome, data and conclusion, limitations of the studies and future work recommendation is included.

5.2 Aims

The aims of the present main study (100% and 50% bone support) were to determine whether RFA, using an Osstell Mentor in an *in-vitro* model can:

- ❑ Determine the specific value above which we can be confident that a bridge is stable.
- ❑ Determine a value below which there is cause for concern – which may translate to a need for more regular monitoring in patients.

5.3 The simulated 100% bone support *in-vitro* study

5.3.1 Aims of the study

The primary aim of this study was to determine whether Resonance Frequency Analysis was a viable technique for objective, non-destructive, testing of bridge stability *in-vitro*.

The secondary aims of this investigation were to:

1. Determine whether there was a specific RFA value above which we could be confident that the bridge was stable *in-vitro*.
2. Determine an RFA value below which there was a high likelihood of bridge cement failure on one abutment *in-vitro*.

5.3.2 Objectives of the study

1. Determine whether resonance frequency analysis (RFA) is capable of measuring fixed bridge stability *in-vitro*.

2. Test two groups of fixed-fixed bridges *in-vitro* – one (test) group mimics cement lute failure on the premolar abutment, the other (control) group mimics a fully cemented restoration.

3. Compare results obtained via RFA (using an Osstell Mentor) and destructive testing using Universal Testing Machine (UTM). Analyse the data sets to determine whether RFA is able to detect the non-cemented abutment *in-vitro*.

4. To determine the difference in Osstell values between fixed bridges on 100% and 50% periodontal bone support models *in-vitro*.

5.3.3 Null hypothesis

1) There were no statistically significant differences in BSQ values between fixed bridges in positive control group and test group on 100% periodontal bone support *in-vitro*.

2) There was no difference in detection, using the Osstell Mentor of the movement of all-metal bridges, when constructed on a periodontal model in the uncemented and cemented *in-vitro* state.

3) There were no differences in Osstell values between fixed bridges on 100% and 50% periodontal bone support models *in-vitro*.

4) There will be no difference in the load required to cause failure, using a UTM test between the test and control groups placed on 100% periodontal bone support models.

5.3.4 Materials and Methods

Before the main study was commenced a series of pilot studies were performed to inform the correct method and protocol for the main experimental study. One operator (KO) performed all tooth preparation to avoid inter-examiner variability and to ensure that the required amount of tooth reduction had been carried out in all prepared teeth.

5.3.4.1 Working cast construction with periodontal model

The conclusion from previous preliminary work was that it was closer to the clinical situation to use working casts with periodontal membrane-like material placed on the root form of acrylic abutment teeth. A method to develop this requirement was performed in order to construct a periodontal model to simulate the procedure more closely to that which would exist in a patient's mouth.

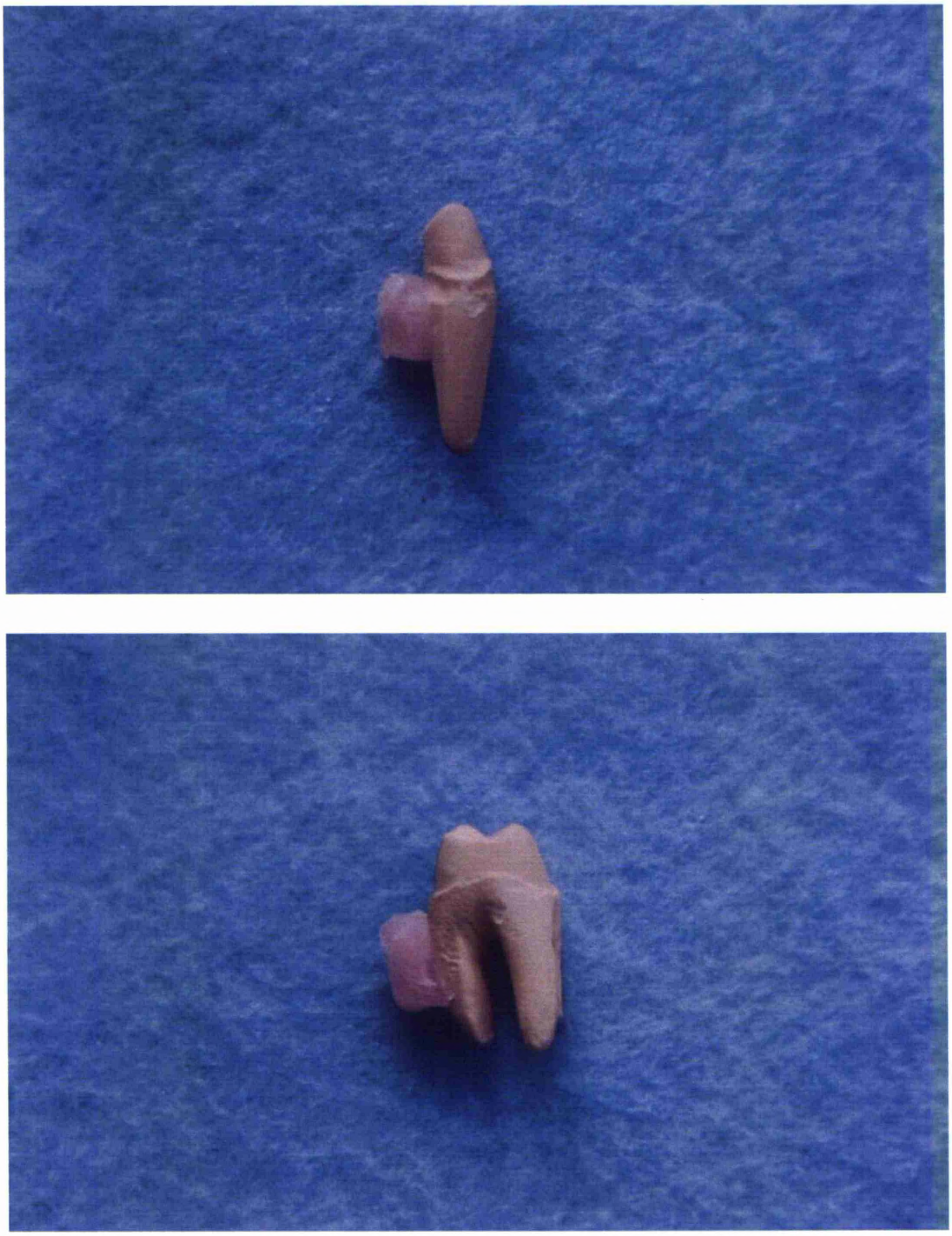
5.3.4.2 Construction of the acrylic abutment teeth

The mould impression (used to construct the working cast) (Figure 16) was poured (not full length) with supra-hard dental stone (Supra-stone, ISO type IV, Kerr, Italy). Starting from upper left canine to upper second molar, left to set at room temperature and then removed from the impression.

Figure 16 The silicone mould index

Using a straight handpiece and cutting disc (double sided) to complete the cut of dental stone in the area just mesial to first premolar (taking care not to damage the finish line around the abutment). Another cut was made distal to first premolar (abutment). This procedure was repeated mesially and distally to the first molar. Each stone piece was carved to resemble (Figure 17) the two and three root form of a first premolar and first molar respectively.

Figure 18 The first molar and premolar carved from dental stone



A plastic denture pot was trimmed 3-4 cm above the base. The teeth, carved from dental stone were placed in a horizontal position in the bowl and were fixed to its base with the help of a wax "sprue" (Figure 18).

Escape vents were placed in the periphery of the occlusal aspect and apically at the root apex of each abutment “tooth” to allow air/gas to escape and prevent later voids in the waxed abutment.

The elastomeric impression material (Z-Dupe, Henry Schein, Italy) was mixed, poured into the cup and left to set for 30min.

After setting, the elastomer was removed from the denture pot. Using a number 11 scalpel blade the impression material was cut above, and in the long axis of the stone tooth (Figure 1). This allowed retrieval of the carved stone teeth from the elastomeric impression material. Now there were two mould cavities that resembled the carved teeth.

Dental base plate wax (Carmel, Champlain, New York) was softened using a Bunsen burner flame and was poured into the elastomer mould cavity (Figure 19), allowed to set at room temperature for 30min (in order to prevent wax distortion) and then the waxed abutment was removed from the impression. This was repeated to obtain the required number of teeth (each of the 50 master casts’ required two abutments, one premolar and one molar)

Figure 18 The waxed tooth being removed from the mould cavity

Figure 19 The mould cavity (top) and the wax poured into mould cavity (bottom)

5.3.4.3 Flasking procedure of waxed abutment

After preparing the wax teeth analogues, they were flasked to produce acrylic teeth. Dental plaster (Surgical plaster, John Winter and Co. LTD, England) (Water/powder ratio 100:60) was mixed and poured into one half of a denture flask. The waxed teeth were placed vertically in the soft dental plaster and left to set at room temperature following which a separating medium was applied to the set plaster.

Dental plaster was mixed and poured into the second half of the denture flask, and then the flasks closed together and the flask was placed into clamps to remove the excess plaster material. These steps were repeated for all the required tooth analogues and the flasks allowed setting at room temperature.

5.3.4.4 De-waxing procedure

The flask was placed in a wax elimination machine (Boil out system 2000, Inter lab, Laboratory Equipment Manufacturers, UK) for one hour to remove the wax. They were opened with the help of sharp knife, and hot water applied to ensure there was no wax residues left in the flask before allowing these to dry.

5.3.4.5 Curing procedure of acrylic tooth analogue and de-Flasking procedure

Heat cure acrylic resin (Betacryl II, Heat cure denture material, Zhan Laboratory, Hennery Schein Company, England) was mixed in a porcelain jar, and allowed to reach the dough stage. The acrylic was placed into the mould cavity, and the flask halves closed together. The flasks were placed in clamps to remove the excess acrylic resin with a gradual increase in the pressure in order to allow the acrylic enter the mould cavity slowly without voids. These flasks were cured in hot water in a heat cure machine for one hour and then the flasks allowed cooling to room temperature.

After cooling the two halves were separated and the acrylic tooth analogues removed from the dental plaster. After removal, they were cleaned, checked off for details and finished.

5.3.4.6 Periodontal ligament like material

Elastomeric impression material (Polyvinyl-siloxane) was used as an analogue for the periodontal membrane. The material is elastic in nature, and has been reported to be stable in an even thickness (Reisbick and Matyas 1975). Rubber based elastomers are widely used in fixed prosthodontics and are highly accurate (Bergman *et al.,* 1972). One coat was determined to be of enough thickness to approximate the periodontal membrane thickness on the natural root surface which, *in-vivo* ranges in width from 0.15 to 0.38mm (Nanci, 2003). Equal amounts of the material (base/catalyst liquid) were mixed in a small bowl and the acrylic tooth held by the occlusal surfaces forceps above the finish line. The roots were dipped into the elastomeric material once, to above the finish line (Figure 20). This was done to ensure that the elastomeric material covered the "cement-enamel junction" of the acrylic tooth surface to allow independent abutment movement, and to prevent interlocking of the analogue tooth structure with dental stone model that could may affect the RFA readings. The material was allowed to set. The thickness of periodontal membrane-like material was one of the variables that considered (from pilot study) while making periodontal models. One coat (0.11 – 0.14 mm) was decided to be sufficient to get an approximate thickness of periodontal ligament and to be similar in all the models to ensure a consistent and repeatable method. The thickness was measured by using callipers by the principle investigator.

5.3.4.7 Working cast with a periodontal membrane (periodontal model)

The intention was to construct periodontal models with acrylic teeth having a periodontal membrane-like material. The modified acrylic analogues were repositioned into the silicone index after being dipped in elastomeric like material (Figure 21) and supra-hard dental stone (Supra-stone, ISO type IV, Kerr, Italy) was mixed and poured into the mould and left to set at room temperature. The periodontal model were recovered (Figure 22) adjusted, cleaned, and finished. This method of producing periodontal model was repeated to obtain fifty models as a sample size for the main study.

Figure 20 The acrylic tooth analogues with silicone impression material applied to the root surfaces

Figure 21 The silicone index with analogues.

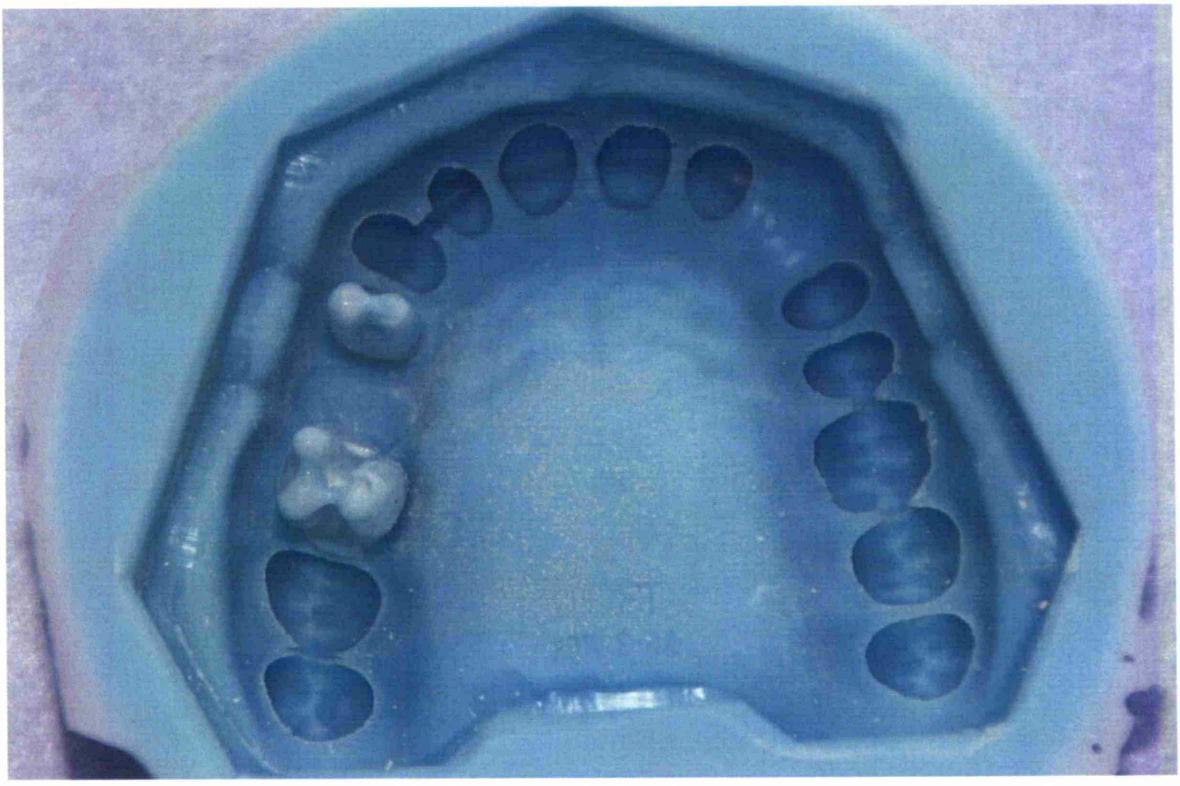
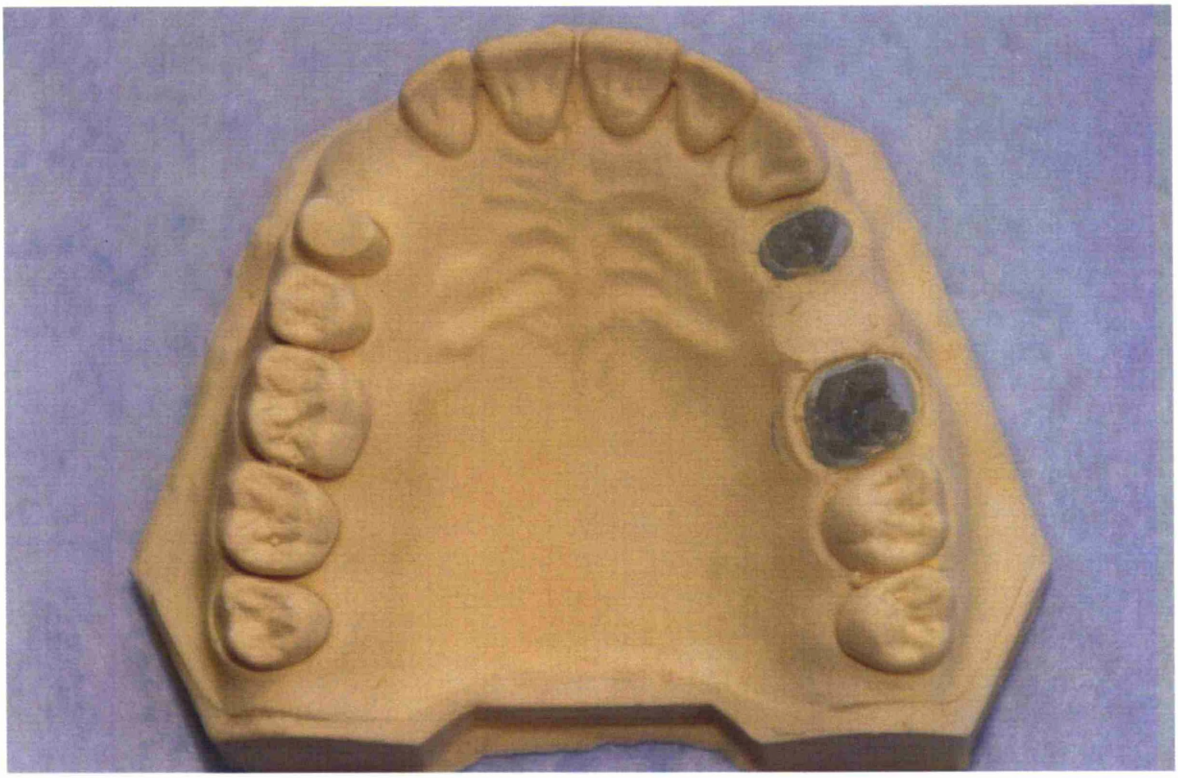
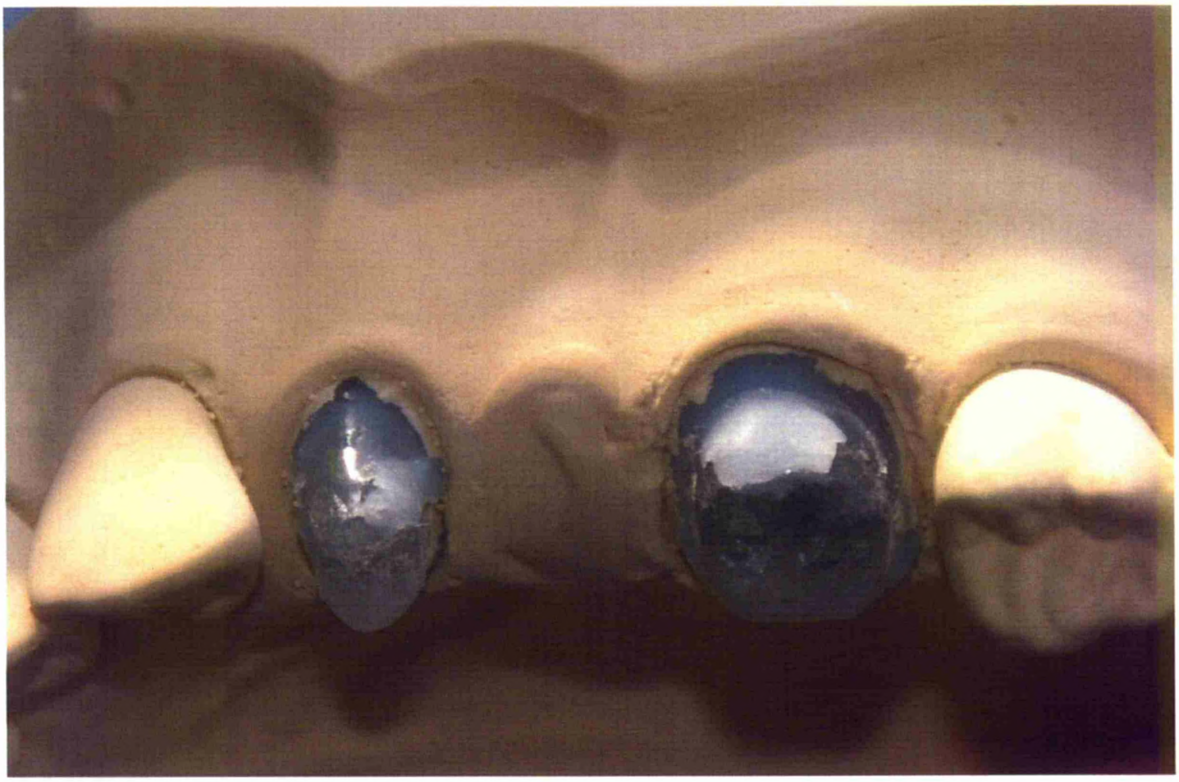


Figure 22 The "periodontal" model





5.3.4.8 Periodontal models

Fifty metal fixed bridges on fifty periodontal models were constructed. Passive fit was ensured to be equal in all bridge work, done with help of finger judgement and by using a luggage scale (Proteam, Kippings Cross, Tonbridge, Kent, UK) to measure how many kilograms were needed to pull-off the uncemented passive-fit fixed bridge in an occlusal direction. A Smartpeg was affixed with help of composite resin material at the mesial side of the molar retainers at the embrasure and at the distal side of the premolars at the embrasure for each fixed bridge. Ten BSQ readings were then taken from the buccal side (as recommended from pilot study) and the mean BSQ values were recorded.

After obtaining the RFA results (expressed as BSQ) from all bridges in the uncemented form, the convergence angles of the preparations were assessed both bucco-palatally and mesio-distally. This was carried out to investigate the amount of the retention (convergence angle) on each acrylic abutment tooth in the fifty models.

The two groups of fixed bridges on the models were tested using the Osstell apparatus by the principle investigator, BSQ values were recorded, and analysed in discussion with a statistician to determine the outcomes of the studies.

5.3.4.9 Convergence angle for models

The convergence angle is the taper of the tooth preparation. This may be considered from the buccal-palatal or from mesial-distal directions. In the current investigation, each abutment on the model was photographed from the buccal and mesial direction (Figure 23) using a Pentax K100D Digital SLR and Tamron 18-200mm zoom lens. The camera was mounted on a tripod and photographs were recorded at a fixed distance using ambient light. These photographs were imported into Powerpoint software (Microsoft) and the convergence angles were derived for each abutment (Figure 24). This was performed by drawing a "best-fit" line onto the preparation surfaces on the buccal and palatal surfaces as well as the mesial and distal surfaces. The angle where the lines crossed each other was measured (convergence angle) and is shown in Tables (11, 12).

5.3.4.9.1 Molar and premolar bucco-palatal convergence angle

Figure 23 Photo of buccal and palatal surfaces of the molar and premolar abutments, red lines illustrate how the convergence angle was derived

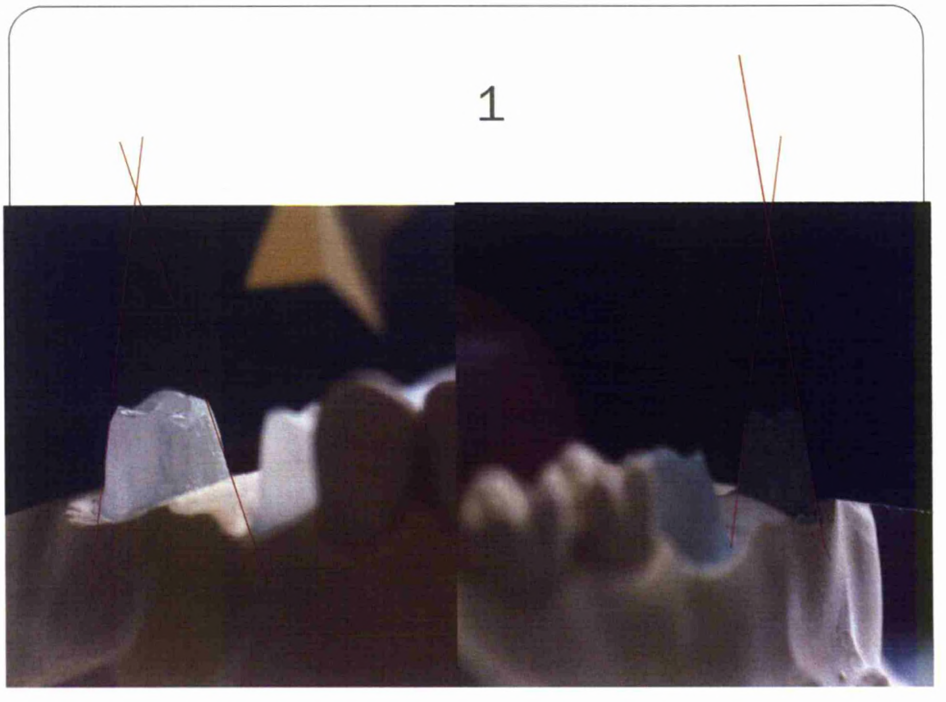


Figure 24 Molar and premolar bucco-palatal convergence angle on model number

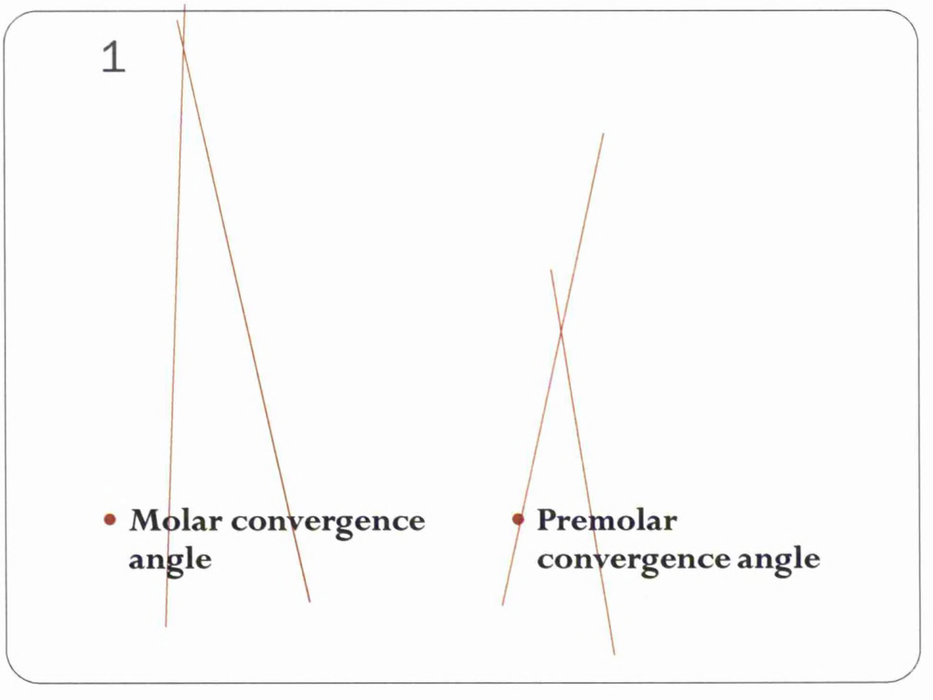


Table 11 Bucco palatal convergence angles by model number

	Bucco-palatal convergence angle on molar (°)	Bucco-palatal convergence angle on premolar (°)
1	15	21
2	15	15
3	17	12
4	22	20
5	20	16
6	21	20
7	16	14
8	19	18
9	19	19
10	20	20
11	20	21
12	21	20
13	22	20
14	18	18
15	18	17
16	21	19
22	22	22
18	15	16

19	15	14
20	15	16
21	15	16
22	16	17
23	18	15
24	17	13
25	14	15
26	18	15
27	16	14
28	17	20
29	16	17
30	16	16
31	17	18
32	14	17
33	16	14
34	16	16
35	19	15
36	22	17
37	18	22
38	23	17
39	17	17
40	18	14
41	18	18
42	18	18
43	20	18
44	16	15
45	18	12
46	18	22
47	23	22
48	16	20
49	20	20
50	16	16

Table 12 shows that the convergence angles ranged from 12° (two premolars on 2 models) to 23° (9 molars and 6 premolars).

The most common/frequent convergence angles were between 14 and 18 degree (within the clinically optimal limits of <20 degree, Jorgensen 1955).

Table 12 Convergence angle distribution in relation to premolar and molar

Convergence angle	Frequency molar	Frequency premolar
12	0	2
13	0	1
14	2	5
15	6	5
16	9	9
17	6	7
18	10	6
19	2	1
20	6	7
21-23	9	6

5.3.4.9.2 Convergence angles from mesial-distal direction of the abutment teeth on periodontal models

The photographs were taken from buccal aspect of each model to assess the mesio-distal convergence angles of the abutments. The mesio-distal convergence angles were then measured on and arranged as in Table 13.

Table 13 Mesial and distal convergence angles

model number	Convergence angles on molar	Convergence angles on premolar
1	24	8
2	14	9
3	14	11
4	18	8
5	18	11
6	9	9
7	17	16
8	15	12
9	15	8
10	17	15
11	11	12
12	19	15
13	16	12
14	13	15
15	25	16

16	14	13
17	18	17
18	18	12
19	13	14
20	13	7
21	15	11
22	16	10
23	16	13
24	9	8
25	13	10
26	13	10
27	18	11
28	12	8
29	14	7
30	13	9
31	10	8
32	18	10
33	13	10
34	12	6
35	13	10
36	10	8
37	19	10
38	8	7
39	15	14
40	15	7
41	18	15
42	20	8
43	23	16
44	23	8
45	16	6
46	18	16
47	18	12
48	15	12
49	15	15
50	12	8

5.3.4.10. Study design

Fifty metal frameworks of fixed bridges were constructed to fit on the fifty periodontal models. These bridges were constructed for the models with simulated 100% bone support. The models were then divided into two stratified groups (Figure 25). The first group (group 1, positive control group, cemented-cemented) consisted of 25 models with fixed bridges, cemented on both retainers (molar and premolar) using zinc phosphate luting cement. The second group (group 2, test group, cemented-free) consisted of 25 models each with one retainer (on the molar tooth) cemented using zinc phosphate luting cement and the other (premolar tooth) left uncemented.

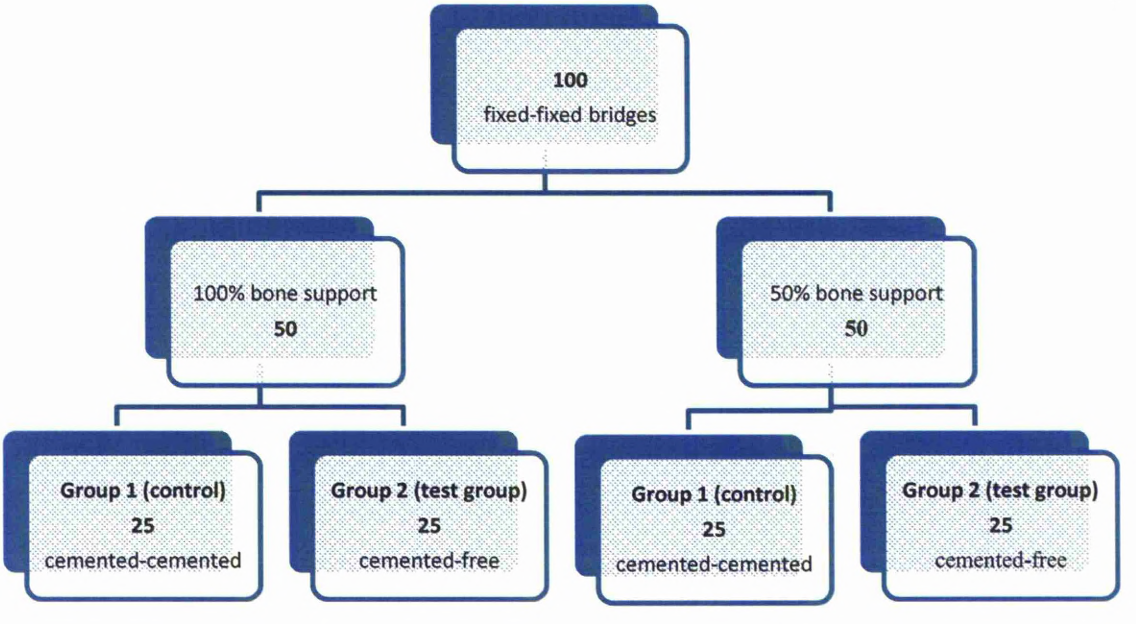
During sorting of the groups, the convergence angles demonstrated a variation of 11° (from 12° to 23°) as shown in Table 13. A Stratified sampling method was adopted to ensure that both test and control groups contained a similar distribution of convergence angles. On original review of the data, four samples were found to be outliers, so a further 4 models were constructed to substitute for these, and a total sample size of 50 models were tested (Figure 25). The allocation to the test and control groups was performed by a second investigator (CCY) to ensure that further assessment was performed "blindly" by the principal investigator. The groups had similar distribution of preparation convergence as well as similar numbers of early, middle and late-constructed models to ensure that there was no "learning curve" effect where the principal investigator's increasing skill in model construction could affect the results. The stratification code was stored by the second investigator.

The second investigator performed the next aspect to ensure subsequent blind assessment. The control group had both retainers cemented to the model using zinc-phosphate cement (SS White, DENTSPLY) mixed to a clinically useable consistency on a chilled glass slab. The cement was applied to the fitting surfaces of the bridge using a flat plastic instrument and placed onto the model using digital pressure. Subsequently, an 8kg weight was used to apply seating pressure to the occlusal surfaces of the bridge for 10 min. After initial set was achieved, excess cement was removed with a dental probe and the model left to set fully.

The test group (group 2, C-F) had cement applied only to the molar retainers before seating in a similar fashion. All excess cement was removed by dental instruments after it reached initial set according to clinical practice. The numbered models were placed in individual sealed polythene bags and stored in the laboratory wardrobe and returned to the principal investigator after 24 hours.

The principal investigator recorded BSQ readings from the buccal direction (as suggested by the pilot study) with the Smartpeg affixed to the bridge adjacent to the premolar and the molar as described previously. Ten BSQ readings were recorded on each occasion and the mean and standard deviations of these readings were calculated.

Figure 25 Flow diagram of test method



5.3.5 Results of the 100% bone support study

In this investigation, all 50 "100% periodontal bone support" models (Figure 25) were constructed using a consistent method to ensure that reproducibility could be achieved. Full details are found in the materials and methods section of Pilot study work (chapter 8, Section 8.4).

To obtain negative control values, BSQ values were obtained, 10 readings from the buccal direction, of all bridges in an uncemented state.

5.3.5.1 BSQ values for uncemented-uncemented fixed bridges (negative control group) on 100% bone support periodontal models

Table 14 demonstrates the mean and standard deviation (SD) BSQ values for uncemented premolar abutments ranged from 28 (0.00) - 56 (0.00) with average BSQ reading of 42. It also shows the BSQ values of uncemented molar abutments were 22 (0.00) – 57 (0.52) with an average BSQ reading of 39.

The majority (88%) of the BSQ readings of the uncemented molar and premolar abutments were below 49. However, 12 models demonstrated higher BSQ values (Table 14), with five models recording 50 or above, at the premolar and seven models at the molar abutments.

Table 14 BSQ values (SD) for uncemented bridges (100% bone support)

	Premolar main BSQ (SD)	Molar main BSQ (SD)
1	32 (0.0)	37 (0.0)
2	30 (0.8)	31 (0.3)
3	28 (0.8)	39 (0.0)
4	38 (1.0)	49 (0.0)
5	53 (0.0)	56 (1.0)
6	39 (1.8)	38 (0.6)
7	41 (0.0)	50 (1.0)
8	39 (0.5)	49 (0.3)
9	39 (0.3)	39 (0.0)
10	39 (0.0)	46 (0.8)
11	47 (1.0)	52 (0.5)
12	38 (0.3)	37 (0.0)
13	37 (0.0)	49 (0.0)
14	38 (0.4)	46 (0.6)
15	47 (2.0)	41 (1.0)
16	49 (0.0)	48 (0.0)
17	39 (0.0)	49 (0.0)
18	40 (1.0)	45 (0.9)
19	30 (0.0)	51 (1.1)
20	48 (0.4)	49 (0.0)
21	35 (0.3)	38 (1.8)
22	56 (0.0)	25 (0.0)
23	54 (0.8)	44 (1.0)
24	35 (0.0)	22 (0.0)
25	30 (0.6)	48 (0.0)
26	35 (0.6)	45 (1.0)
27	53 (0.0)	45 (0.6)
28	37 (0.9)	37 (0.0)
29	28 (0.0)	44 (0.0)
30	49 (0.0)	57 (0.5)
31	48 (0.0)	37 (0.0)
32	44 (0.0)	51 (0.0)
33	37 (0.4)	39 (0.8)
34	39 (0.0)	39 (0.0)
35	30 (0.0)	44 (0.8)
36	51 (1.6)	50 (1.0)
37	36 (1.0)	30 (0.8)
38	30 (0.0)	43 (0.8)
39	37 (2.0)	37 (0.0)
40	42 (1.0)	44 (0.0)
41	28 (0.0)	37 (0.0)
42	39 (0.0)	39 (0.0)
43	44 (0.0)	39 (0.0)
44	43 (0.5)	45 (1.0)
45	47 (0.9)	38 (1.0)

46	43 (0.4)	36 (0.8)
47	39 (0.0)	38 (0.0)
48	35 (0.6)	40 (0.6)
49	35 (0.0)	35 (0.8)
50	43 (0.9)	46 (0.0)

5.3.5.2 BSQ values for test and positive control group (100% bone support)

Group 1, with both abutments cemented as described previously was the cemented-cemented (C-C) positive control group (25 models). Group 2 consisted of the cemented-free (C-F) was the test group (25 models). The BSQ readings (10 readings from the buccal direction from the premolar and molar abutments) (Table 15) were all recorded 7 days after cementation. The investigator was unaware of which group the models had been assigned to and recorded the results by model number.

When all values had been recorded for BSQ and universal testing machine (UTM) testing (see later), the "code" was released to assign the data to the control or test groups for initial analysis.

In group 1 (Positive control group, C-C), Table 15 demonstrates that there are three mean BSQ readings on premolar below 62, with only one BSQ reading on a molar below a value of 62. 98% (53/54) of molar BSQ values were above 62 values.

In group 2 (test group, C-F), Table 15 shows that mean premolar BSQ values range from 36 to 78 with an average of 57, while in molar mean BSQ values it ranges from 40 to 81 with an average of 60. The data also demonstrate that 59% (16/27) of premolar mean BSQ readings were below 62, where as 88% (24/27) of molar mean BSQ readings were above 62.

Table 15 Mean BSQ values for positive control group (group 1, C-C) and test group (group 2, C-F)

Group	premolar BSQ (SD)	molar BSQ (SD)
1	79 (0.6)	77 (0.9)
1	73 (0.9)	86 (2.2)
1	57 (0.0)	72 (0.4)
1	76 (1.4)	75 (0.2)
1	79 (0.7)	85 (1.0)
1	43 (1.0)	44 (0.3)
1	77 (1.7)	74 (1.5)
1	71 (3.4)	76 (0.7)
1	68 (0.6)	62 (0.1)
1	69 (0.5)	76 (0.5)
1	75 (0.1)	79 (0.4)
1	70 (8.1)	63 (0.0)
1	70 (1.9)	66 (6.0)
1	73 (1.3)	64 (1.8)
1	72 (4.5)	65 (0.6)
1	69 (7.0)	67 (3.1)
1	67 (2.9)	65 (0.6)
1	83 (0.1)	75 (1.0)
1	86 (4.5)	68 (4.1)
1	43 (1.0)	80 (4.7)
1	71 (0.6)	73 (2.0)
1	82 (2.0)	80 (4.7)
1	80 (0.6)	85 (5.5)
1	78 (8.7)	80 (4.6)
1	74 (8.7)	71 (4.0)
1	71 (0.4)	65 (2.4)
1	70 (0.5)	68 (1.4)
2	42 (0.7)	66 (3.8)
2	61 (0.0)	70 (0.0)
2	78 (0.0)	67 (0.0)
2	41 (0.5)	75 (0.7)
2	40 (1.3)	40 (1.0)
2	40 (1.9)	72 (3.1)
2	36 (0.5)	81 (5.8)
2	75 (0.0)	71 (3.5)
2	45 (0.5)	71 (4.0)
2	70 (0.0)	67 (0.2)
2	42 (0.0)	65 (0.0)
2	44 (0.4)	75 (0.3)
2	81 (0.0)	77 (0.4)

2	46 (1.8)	67 (0.6)
2	76 (2.0)	71 (3.9)
2	67 (4.4)	70 (1.0)
2	67 (1.5)	67 (0.1)
2	68 (1.6)	64 (1.1)
2	67 (3.2)	65 (4.6)
2	72 (4.5)	73 (7.5)
2	63 (4.4)	62 (1.7)
2	74 (0.3)	41 (1.1)
2	61 (3.2)	63 (1.7)
2	42 (1.1)	41 (1.1)
2	54 (6.6)	67 (2.5)
2	76 (1.0)	65 (4.0)
2	42 (0.1)	71 (3.5)

5.4 Universal Testing Machine (UTM) investigations

This *in-vitro* test used the bridges previously assessed by RFA in a Universal Testing Machine (UTM) to pull the bridges from the abutment teeth and record the forces to failure in Newtons. This allowed comparison of the BSQ values with a widely-used, but destructive, testing regimen.

5.4.1 Aims

1. To measure the amount of force (N) required removing the bridges from the models *in-vitro*.
2. To determine if these forces could identify statistically significant differences between the test (cemented-free) and positive control (cemented-cemented) groups.
3. To compare the loads to failure (N) with the resonance frequency analysis (RFA) results.

5.4.2 Materials and Methods

To simulate the tensile load that could occur in the oral environment, the UTM was used in extension mode. This involved placing an increasing load/force to the bridges that attached to the UTM (Lloyd instrument Ltd, Steyning Way, Bognor Regis, West Sussex, UK). A 500 (N) load cell (with 0.5% sensitivity) was selected and a cross-head speed of 10mm/min chosen. Maximum biting forces can reach 450N (Huysmans *et al.*, 1992). Kovarik *et al.*, (1992) applied a load of 334N to both the buccal and lingual sides of premolar specimen in their study so it was felt that a 500N load cell was most likely to be within the required range. Many variations in crosshead speeds have been selected for *in-vitro* testing of dental restorations, from 0.025mms^{-1} [1.5mm/min] (Heydecke *et al.*, 2002) to 135mms^{-1} [8,100mm/min] (Saunders 1986). The latter (who investigated the impact of these speeds on resin bonded bridges) reported that this speed was chosen to simulate maximum chewing speed.

The speed of the movement developed by the mandible as it moves away from the maxilla varies while/during chewing cycle and it different between individuals. The rate of the movement decreases as it approaches the teeth. The proper mandibular movement time varies but it may vary between 64 and 135mm/s (Bates *et al.,* 1976).

However, there is no clear clinical evidence to support any of these speeds in the testing of dental restorations.

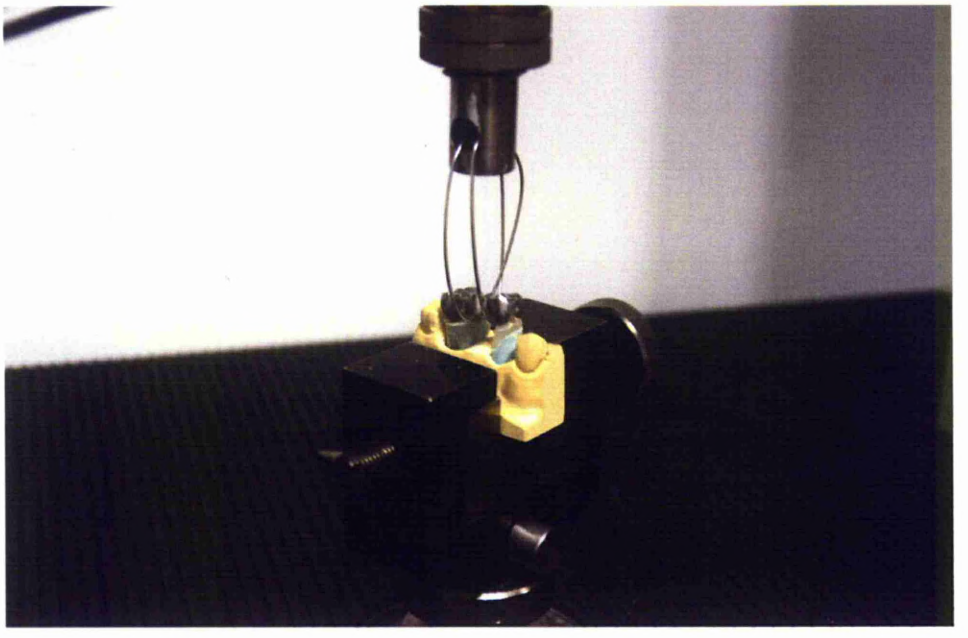
5.4.2.1 The specimens

The specimens in this study were the same stone models of a partially dentate maxillary arch, and all-metal bridges, which had previously been used for the RFA analysis. All UTM testing took place "blind" i.e. before the test and control groups were decoded.

5.4.2.2 Preparation of the models for tensile testing

The model, containing the abutment analogues and the metal bridge superstructure, was sectioned into pyramidal shaped blocks of 20 mm width and 30 mm in length to fit into the UTM. To allow testing, without an upper clamp dislodging the prosthesis prior to loading, each fixed bridge had an orthodontic wire wrapped under the pontic and threaded through a hole in the upper member of the UTM (Figure 26). This was to allow a more vertical application of tensile forces. The sectioned cast was fixed into the lower part of the machine and the UTM calibrated to allow a passive stage before testing (N=0.00) as in Figure 27.

Figure 26 Trimmed stone model with orthodontic wire fixed in the UTM



5.3.2.3 Tensile testing of specimens

The test involved placing a controlled load to the fixed bridge samples until failure occurred. A 500 (N) load cell and a cross-head speed of 10mm/min were selected for all specimens. A first model was used to assess the appropriateness of the load cell. The bridge did not decement but significant abutment "root extraction" occurred and confirmed that the correct load cell was being used.

An increasing load was then applied to each model until complete failure occurred. This took two forms; either the fixed bridge debonded from the model, or the abutment was "extracted" from the stone base. Photographs of representative samples were recorded after failure and the specimens removed and assessed for any debonding or base damage.

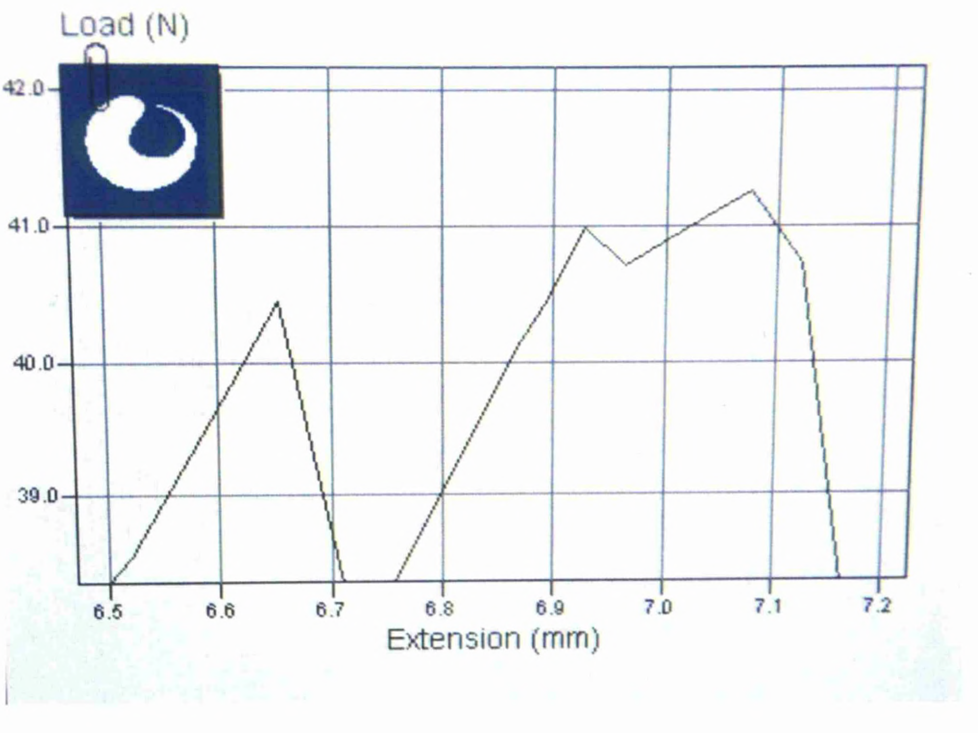
However, several problems occurred before and during testing: The distal aspect of one model was found to have fractured before testing.

Nine models fractured while being prepared for/during testing and therefore could not be loaded correctly.

5.4.3 Results of UTM tensile testing

All the results of the extension force testing were recorded onto a personal computer that was connected to the Universal Testing Machine. The data was then saved into Microsoft Excel and graphs produced that could be interpreted and analysed to identify the amount of force (N) that was required to deboned or extract the fixed bridge (Figure 27). Each model had the mode of failure recorded (Table 16) as bridge deboned or extraction and which abutment was affected, or both of them. The amount of force at failure was identified to record how much force (N) was needed to deboned or extract. After decoding of the specimen numbers, the data was further analysed with respect to whether bridge was in the test group (cement-cement) or control group (cement-free) and whether this affected the model itself.

Figure 27 Graph obtained from the computer connected to the Lloyd UTM showing a trace demonstrating force to failure (N) of fixed-fixed bridges on periodontal models.



5.4.3.1 Preliminary analysis

Twenty two percent (11/50) of the fixed bridges (in group 1 and group 2) failed by debonding on molar as in Table 17, where as 60% (30/50) of the bridges failed by both abutments being extracted. Whether one or two abutments were extracted and one fixed bridge failed by complete debonding as shown in Table 16.

Figure 28 bridge debonded in positive control group (group 1, C-C)

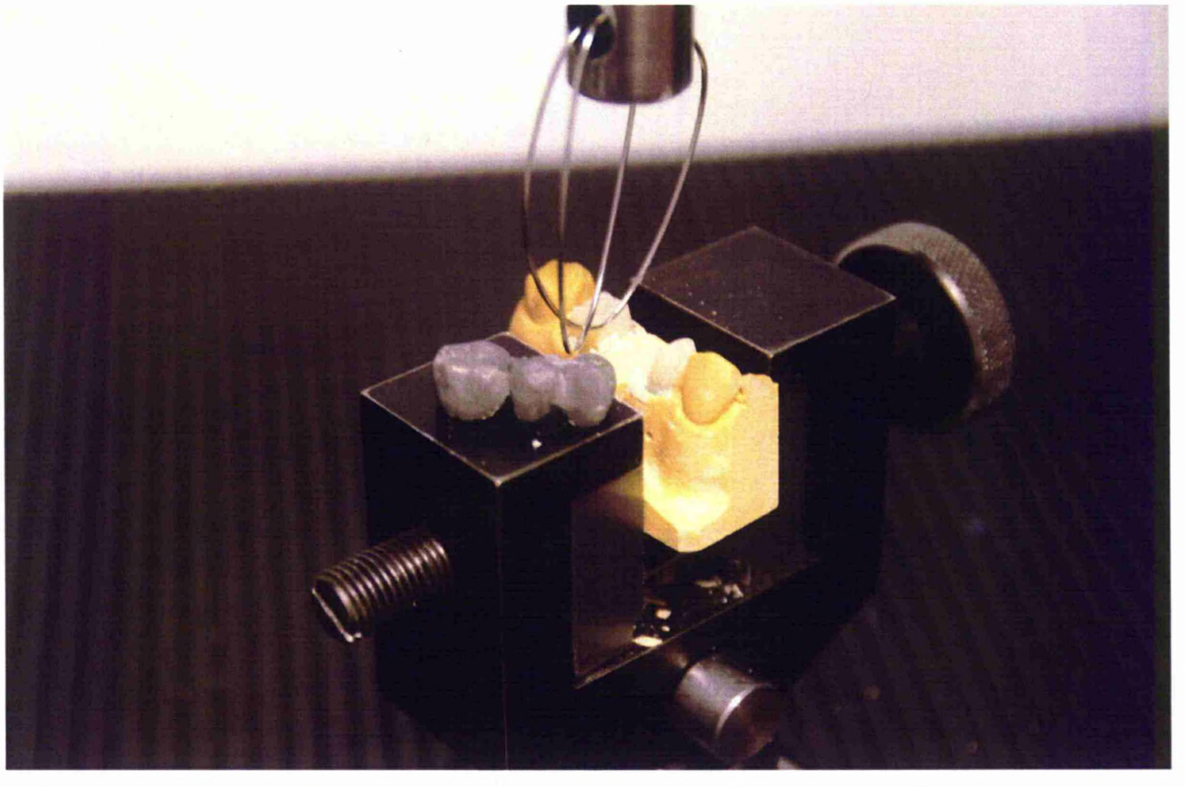


Figure 29 Extraction of molar abutment in test group (group 2, cemented-free)

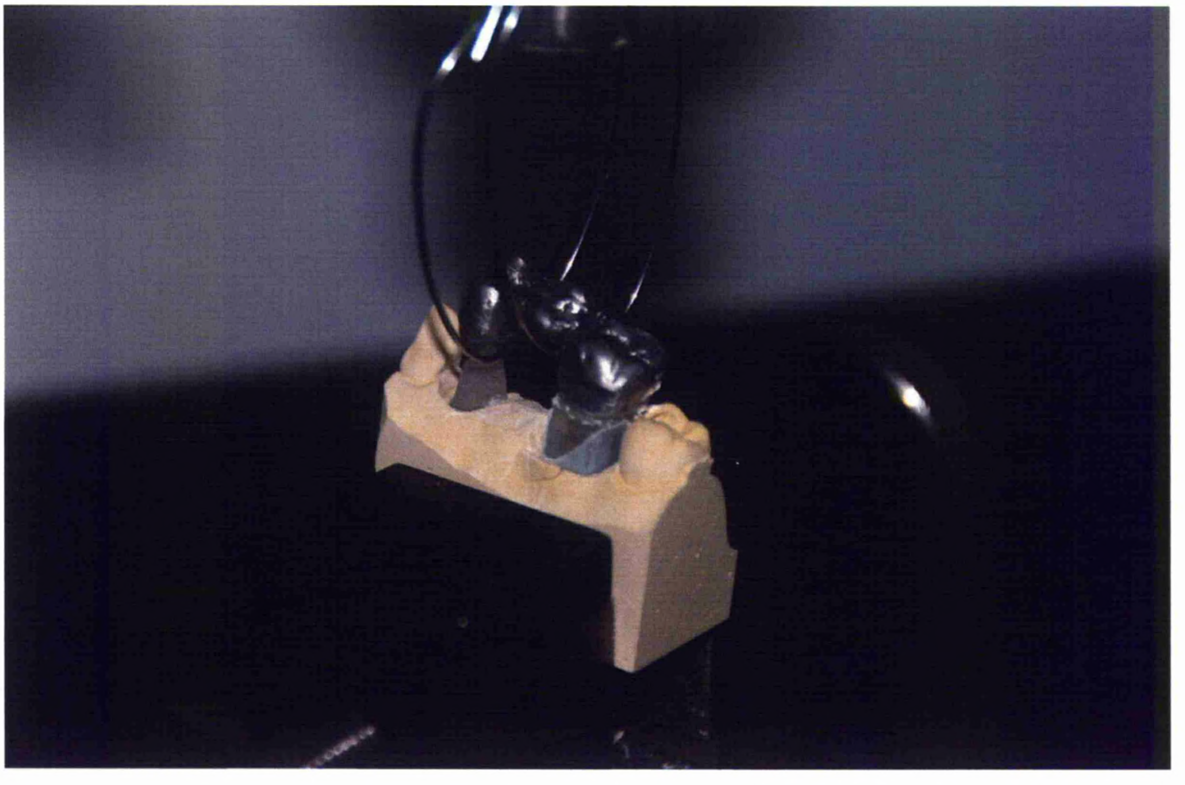


Figure 30 Fracture of the stone model with debonded molar and extracted premolar

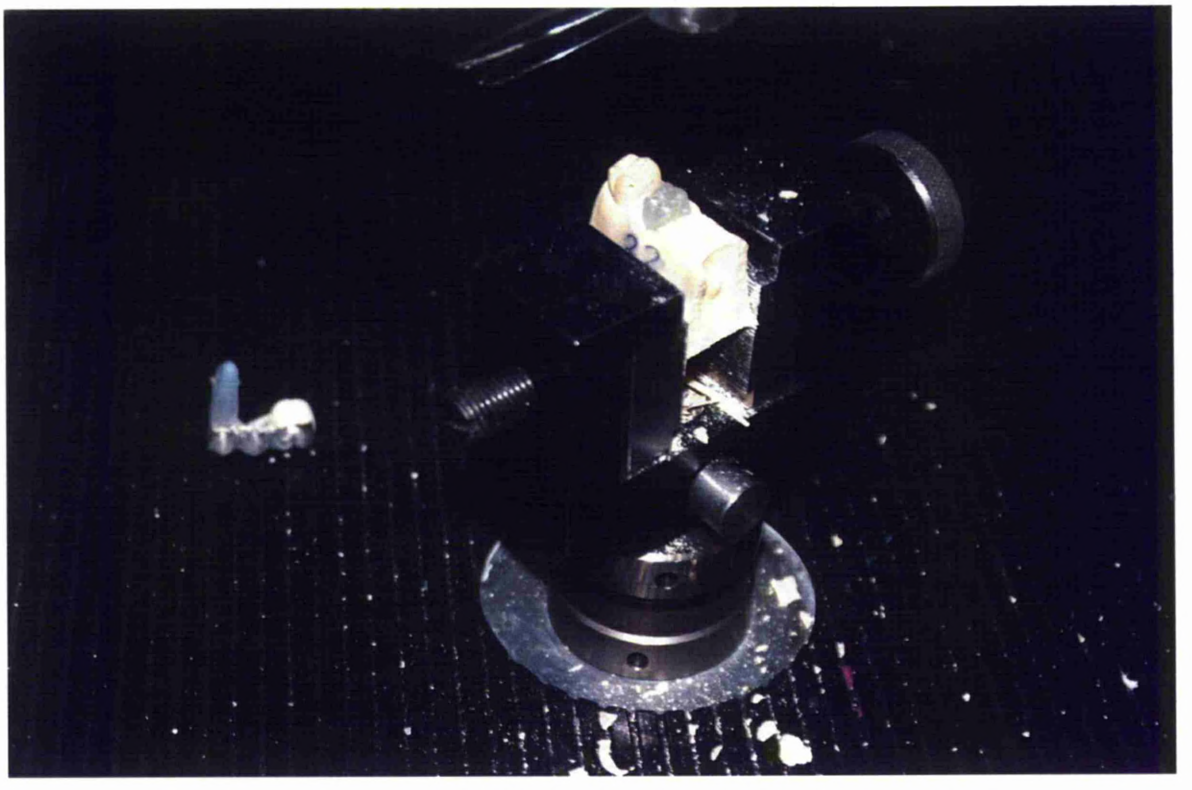


Figure 31 Excel graph of a specimen (test group, specimen number 5) with low force to failure

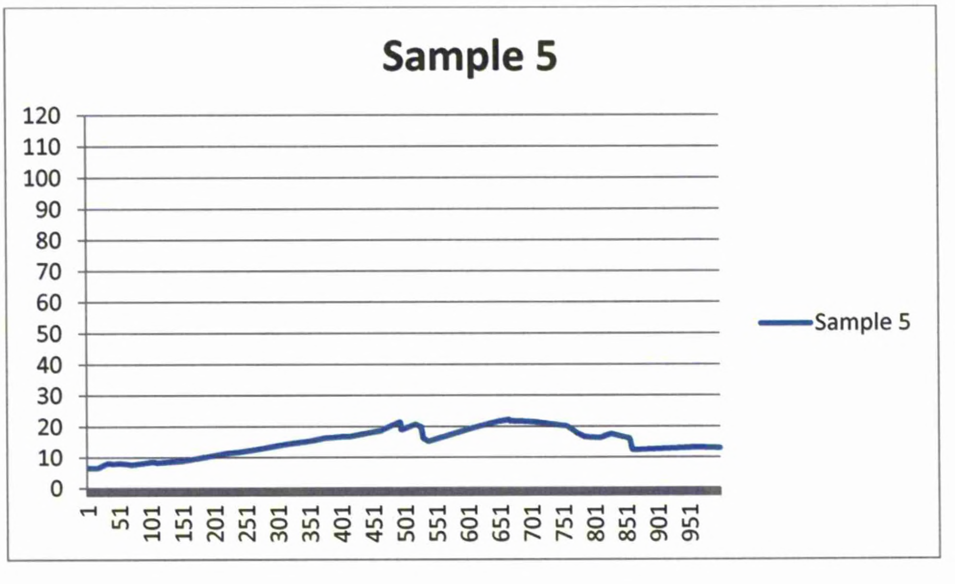


Table 16 Summary of results of UTM tensile testing

Group 1 (positive control group, cemented-cemented, C-C) Mode of failure E (Extracted) D (Debonded) # (Fractured base)		**Group 2 (test group, cemented-free, C-F)** Mode of failure		**Group 1** Load at failure (N)	**Group 2** Load at failure(N)
Molar	Premolar	Molar	Premolar		
E	E	E	E	41	41
E	E	E	E	117	22
D	D	E	E	37	9
D	E	E #	E	14	22
E	E	E #	E	97	9
D	E #	E #	E	119	36
D	E #	E	E	99	23
E	E #	E	E	64	28
E	D	E	E	75	60
E	E	E #	E	109	23
E #	E	D	E	96	36
D	E # buccal	E	E	84	18
D	E #	D	E	104	55
D	E #	E	E	78	17
E	E	D	E	90	62
E	E	E #	E	112	75
E	E #	E #	E	69	11
D	E	E	E	35	50
D	E	D	E	24	30
D	E	E	E	28	22
D	E	E	E	108	25
E	E	E #	E	29	20
D	E	D #	E	33	20
E	E	E	E	92	66
E	E #	D	E	105	28

Although some of the debonding (D) occurred in cemented-cemented models (group 1, positive control group) it was also experienced in models with the cemented-free (group 2, test group) group as shown in Table 16. The debonded models were found to be in the cemented-cemented and cemented-free bridges. However, Table 16 demonstrates that extraction of both abutments (E E) occurred in 60% (30/50) of the specimens tested.

5.3.3.2 The amount of force applied on models

Only three bridges (6%) debonded completely. A further five out of fifty models (10%) were debonded from one side and not from the other, despite being in the cemented-cemented group. The amount of force needed for debonding varied amongst specimens (Table 16). This appears to have been dependent upon the number of abutments cemented. Twelve specimens (48%) in group 1 (positive control group, C-C) were debonded at loads of above 82 and 120 N. However, most of the group 2 (test group, C-F) specimens failed by extraction from one (6/25 models, 24%) or both ends (19/25, 76%) at loads below 75N. This mode of failure might be because of the presence of periodontal-like membrane materials (Figure 36) allowing extraction of one abutment and subsequent tilting with a torqeuing rather than a tensile effect.

5.3.3.3 Fracture of stone models while loading

In group 1 (positive control group, C-C), three models (3/25, 12%) failed by initial fracture at the premolar sites (Figure 30) of the stone followed by final complete fracture of the base with extraction of the abutments at a high load (64, 69, 105 N) (Table 16). However, no debonding was noted in any of these specimens.

In case of the group 2 (test group, C-F) 7 models (7/25, 28%) were failed by extraction and fracture at the molar sites of the stone model at a low load (22, 9, 36, 23, 75, 11, 20 N). However, a slight fracture of the stone base had been noted in one of these stone models before starting the tensile testing.

The multiple modes of fracture and failure of bonding within the groups suggest that the data obtained from the UTM is highly unreliable and so is not amenable to meaningful statistical analysis.

5.5 The 50% periodontal bone support *in-vitro* study

5.5.1 Aim of the study: to determine whether a Resonant Frequency Analysis (RFA) device could be used to detect early failure, *in-vitro*, of a fixed bridge on models with simulated 50% bone support.

5.5.2 Objectives of 50% bone support *in-vitro* study

1. Determine whether resonance frequency analysis (RFA) is capable of detecting failure of fixed bridge stability, *in-vitro*, on models with simulated 50% bone support.

2. Compare the results with those obtained with simulated 100% bone support.

5.5.3 Materials and Methods

The "50% bone support" models were made following the same methods of construction as the 100% periodontal bone support models described previously. On this occasion however, half the height of the root surfaces was kept free of dental stone in order to simulate 50% periodontal loss that may be found in a patient's mouth. Analysis of the models demonstrates that the mean root length covered was 50 % ± 5%.

The previously tested fixed bridges and acrylic tooth analogues were recovered, after UTM testing from the 100% support models in an attempt to ensure the consistency of methods and reduce variables in the study.

Using the same methodology as before and after constructing the models, these were, again, given to a second operator to have the bridges cemented. Half of the models (Figure 18) had the bridges cemented using zinc phosphate cement on both abutments whilst the other half were left without cement on the premolar abutment to mimic cement lute failure. After seven days the models had BSQ's recorded.

Each abutment on the model was photographed from the buccal and mesial surfaces, using a digital camera and photographs were recorded at a fixed distance. These photographs were imported into Powerpoint software (Microsoft) and the convergence angles calculated by drawing a line onto the preparation surfaces on the buccal and palatal surfaces as well as the mesial and distal surfaces. The convergence angle where the lines crossed each other was measured in all 50 models.

5.5.4. Study design

The 50 models were again divided (Figure 25) into two groups each consisting of 25 models with one fixed bridge each. Group 1 remained the positive control (C-C) and group 2 the test group (C-F). Ten BSQ readings were taken from the buccal aspect with the Smartpeg fixed at the molar or premolar site (mean values are shown in Table 18). All records were taken "blind" before the code was broken and the specimens assigned to the relevant group.

5.5.5 Results 50% periodontal bone support *in-vitro*

5.5.5.1 BSQ values of uncemented 50% bone support models

Ten BSQ readings of uncemented bridges on the 50% bone support models (50 models) were taken from the buccal surface. The mean values of these negative controls are shown in Table 17. The mean BSQ readings on the molar were 43 (range 28-58) and premolar 43 (range 28-57).

Table 17 BSQ values of 50% bone support bridges – non cemented premolar and molar

	Mean BSQ Value (SD)	**Mean BSQ value (SD)**
Specimen no.	**Molar**	**Premolar**
1	30 (0.0)	46 (0.1)
2	42 (0.0)	46 (0.8)
3	55 (0.6)	39 (0.6)
4	37 (0.1)	32 (0.0)
5	37 (0.0)	57 (0.3)
6	56 (0.5)	57 (0.1)
7	35 (0.0)	28 (0.0)
8	46 (0.3)	35 (0.1)
9	49 (0.1)	46 (2.3)
10	37 (1.2)	39 (1.1)
11	28 (3.4)	32 (0.8)

12	35 (0.8)	37 (0.2)
13	35 (0.9)	32 (0.9)
14	39 (0.7)	35 (0.0)
15	56 (0.0)	39 (0.6)
16	35 (0.0)	32 (0.1)
17	41 (0.1)	28 (0.3)
18	35 (0.0)	39 (2.6)
19	41 (0.2)	32 (0.0)
20	41 (0.1)	35 (0.9)
21	28 (0.0)	32 (1.7)
22	39 (0.9)	30 (3.4)
23	28 (2.6)	41 (6.8)
24	41 (6.5)	37 (4.3)
25	37 (3.2)	32 (1.5)
26	30 (0.0)	35 (2.5)
27	39 (0.3)	30 (0.0)
28	49 (0.0)	42 (0.0)
29	30 (0.1)	32 (0.3)
30	39 (0.7)	41 (0.7)
31	58 (0.0)	46 (1.8)
32	37 (0.8)	30 (2.3)
33	41 (0.7)	33 (1.6)
34	55 (1.0)	46 (0.0)
35	37 (2.4)	32 (0.4)
36	30 (0.9)	28 (0.1)
37	56 (0.5)	42 (0.9)
38	35 (0.1)	30 (0.7)
39	35 (0.0)	32 (0.0)
40	37 (0.2)	41 (2.1)
41	30 (2.1)	28 (0.0)
42	35 (0.6)	32 (2.1)
43	37 (0.4)	30 (0.1)
44	37 (0.8)	32 (0.0)
45	30 (0.2)	28 (0.6)
46	30 (0.9)	42 (0.0)
47	41 (0.5)	37 (0.3)
48	30 (0.20	44 (2.4)
49	35 (0.1)	32 (0.0)
50	37 (0.0)	39 (0.0)

5.5.5.2 Mean (SD) BSQ values of positive control group and test group (50% bone support models).

In group 1 (control group, cemented-cemented, C-C), Table 18 shows that the BSQ readings from the premolar ranged from 51 to 85 with 96% (24/25) of BSQ values in this group being greater or equal to 62. The BSQ readings from the molar ranged from 37 to 84 with 92% (23/25) of BSQ value being greater to 62.

In group 2 (test group, cemented-free, C-F), Table 18 shows that premolar BSQ values range from 42 to 66, while in the molar they range from 32 to 85.

It also shows 96% (24/25) of premolar BSQ readings were below the value of 62, where as 92% (23/25) of molar BSQ readings were above 62.

Table 18 50% bone support mean and SD BSQ values of group 1 (positive control group, C-C) and group 2 (test group, C-F)

Group	Mean BSQ value premolar SD	Mean BSQ value molar SD
1	72 (0.3)	67 (0.0)
1	77 (0.0)	70 (0.0)
1	51 (0.1)	76 (0.4)
1	85 (0.0)	82 (0.2)
1	62 (0.2)	61 (0.0)
1	84 (0.0)	84 (0.0)
1	69 (0.4)	72 (0.4)
1	67 (0.0)	75 (0.6)
1	64 (0.0)	64 (0.8)
1	61 (0.8)	60 (0.2)
1	68 (0.0)	55 (0.0)
1	73 (0.0)	72 (1.0)
1	64 (0.4)	81 (0.0)
1	76 (0.3)	62 (0.0)
1	66 (1.0)	67 (0.4)
1	66 (0.0)	61 (0.2)
1	65 (0.2)	76 (0.4)
1	65 (0.0)	61 (0.0)
1	70 (0.0)	75 (0.0)
1	63 (0.6)	65 (0.2)
1	53 (0.4)	37 (0.8)
1	70 (0.8)	75 (0.6)
1	68 (0.4)	69 (0.0)
1	67 (0.0)	75 (0.4)
1	70 (0.0)	73 (0.2)

2	52 (0.0)	76 (0.0)
2	42 (0.2)	49 (1.2)
2	44 (0.0)	70 (0.8)
2	42 (0.4)	76 (0.0)
2	65 (0.4)	63 (0.4)
2	60 (0.0)	65 (0.0)
2	58 (0.0)	71 (0.4)
2	48 (0.2)	64 (0.3)
2	52 (0.8)	32 (0.0)
2	45 (0.0)	66 (0.0)
2	51 (0.2)	80 (0.2)
2	46 (0.0)	67 (0.0)
2	42 (0.0)	63 (1.0)
2	45 (0.4)	71 (0.0)
2	43 (0.0)	85 (0.0)
2	43 (0.0)	70 (0.0)
2	42 (0.0)	74 (1.0)
2	45 (0.4)	73 (0.0)
2	41 (0.6)	63 (1.2)
2	48(0.0)	80 (0.8)
2	43 (0.0)	70 (0.4)
2	44 (0.2)	75 (0.0)
2	48 (0.0)	61 (0.0)
2	58 (0.0)	62 (1.4)
2	49 (0.2)	68 (0.0)

5.6 Statistical analysis

The code was broken and the data assigned to control (group 1, cemented-cemented, C-C) and test (group 2, cemented-free, C-F) groups.

The data was analysed using Minitab 15.1.1 statistical software package (Minitab Inc. USA). On preliminary viewing using a dot plot of the data it was noted that the data were not normally distributed so non-parametric analysis was subsequently used.

To perform the statistics, Minitab-15 software was downloaded from the Liverpool University website. A non-parametric Kruskal Wallis test was used in the present study, comparing more than two groups of data.

5.6.1 Kruskal-Wallis test (100% bone support): premolar BSQ

To assess data gained from the Smartpeg at the premolar abutment, the Kruskal-Wallis test was selected.

Kruskal-Wallis Test: premolar

Kruskal-Wallis Test Smartpeg at premolar

C1	N	Median	Ave Rank	Z
1	25	72.00	33.8	2.96
2	25	63.00	21.2	-2.96
Overall	50		27.5	

H = 8.75 DF = 1 P = 0.003
H = 8.77 DF = 1 P = 0.003 (adjusted for ties)

This demonstrates that there is a highly statistically significant difference (P<0.005) between group 1 and group 2.

5.6.2 Kruskal-Wallis Test (100% bone support): molar BSQ

To assess data gained from the Smartpeg at the molar abutment, the Kruskal-Wallis test was selected

Kruskal-Wallis Test: molar
Kruskal-Wallis Test Smartpeg at molar

C1	N	Median	Ave Rank	Z
1	25	73.00	32.0	2.09
2	25	67.00	23.0	-2.09
Overall	50		27.5	

H = 438 DF = 1 P = 0.036
H = 4.40 DF = 1 P = 0.036 (adjusted for ties)

It can be seen that there was a statistically significant difference (P<0.05) between group 1 and group 2.

5.6.3 Kruskal-Wallis Test (50% bone support): Premolar BSQ

Kruskal-Wallis Test: 50% premolar
Kruskal-Wallis Test Smartpeg at 50% premolar

C1	N	Median	Ave Rank	Z
1	25	67.00	36.2	5.19
2	25	45.00	14.8	-5.19
Overall	50		25.5	

H = 26.94 DF = 1 P = 0.000
H = 26.99 DF = 1 P = 0.000 (adjusted for ties)

This demonstrates that there is a highly statistically significant difference (P<0.000) between group 1 and group 2 with 50% "bone" support.

5.6.4 Kruskal Wallis Test (50% bone support): Molar BSQ

Kruskal-Wallis Test Smartpeg at 50% molar

C1	N	Median	Ave Rank	Z
1	25	70.00	25.8	0.13
2	25	70.00	25.2	-0.13
Overall	50		25.5	

H = 0.02 DF = 1 P = 0.900
H = 0.02 DF = 1 P = 0.899 (adjusted for ties)

No statistically significant difference (P<0.90) was found between the C-F group and C-C group molars in 50% bone support.

5.6.5 Receiver Operating Characteristic (ROC) curve for 100% bone support fixed bridges

Receiver operating characteristic (ROC) analysis has been recommended by several authors as standard practice for test evaluation studies (Gardner and Greiner 2006). Some of the advantages of ROC are that it can decide which threshold (cut-off point) is optimal for a given decision making problem. It can also directly compare different methods by looking to their threshold and graphs.

The first use of ROC method was in the 1960s to assess an image device (Zweig and Campbell 1993), then after that it was used widely to evaluate clinical tests (Metz 1978).

The area under ROC curve (AUC) provides an overall summary statistic of test accuracy, and it ranges between 0.5 and 1. A perfect test has AUC of 1 and a less accurate test has 0.5. Based on this data, the following guidelines have been suggested (Greiner *et al.*, 2000) as the range of AUC values;

Low (0.5<AUC<0.7),

Moderate (0.7<AUC<0.9)

High (0.9<AUC<1)

Where the perfect test exists when AUC=1 (Swets 1988).

Table 19

Coordinates of the ROC Curve (100% bone support)

Test Result Variable(s):premolar BSQ

Positive if Greater Than or Equal To	Sensitivity	Specificity	1 – Specificity	Sensitivity + Specificity
35.0000	1.000	.000	1.0	1.000
38.0000	1.000	.037	1.0	1.037
40.5000	1.000	.111	0.9	1.111
41.5000	1.000	.148	0.9	1.148
42.5000	1.000	.296	0.7	1.296

43.5000	.926	.296	0.7	1.222
44.5000	.926	.333	0.7	1.259
45.5000	.926	.370	0.6	1.296
51.5000	.926	.407	0.6	1.333
59.0000	.889	.407	0.6	1.296
62.0000	.889	.481	0.5	1.370
65.0000	.889	.519	0.5	1.407
67.5000	.852	.630	0.4	1.481
68.5000	.815	.667	0.3	1.481
69.5000	.741	.667	0.3	1.407
70.5000	.630	.704	0.3	1.333
71.5000	.519	.704	0.3	1.222
72.5000	.481	.741	0.3	1.222
73.5000	.407	.741	0.3	1.148
74.5000	.370	.778	0.2	1.148
75.5000	.333	.815	0.2	1.148
76.5000	.296	.889	0.1	1.185
77.5000	.259	.889	0.1	1.148
78.5000	.222	.926	0.1	1.148
79.5000	.148	.926	0.1	1.074
80.5000	.111	.926	0.1	1.037
81.5000	.111	.963	0.0	1.074
82.5000	.074	.963	0.0	1.037
83.5000	.037	.963	0.0	1.000
85.0000	.037	1.000	0.0	1.037
87.0000	.000	1.000	0.0	1.000

Table 19 shows sensitivity, specificity, and 1-specificity (false negative ratio) each separately. The values of sensitivity start from 1 and decrease as we go further down in Table 19, while specificity decreases as we go up. 1-specificity begins from 1.0 and decreases to reach 0.0 at the bottom of the table.

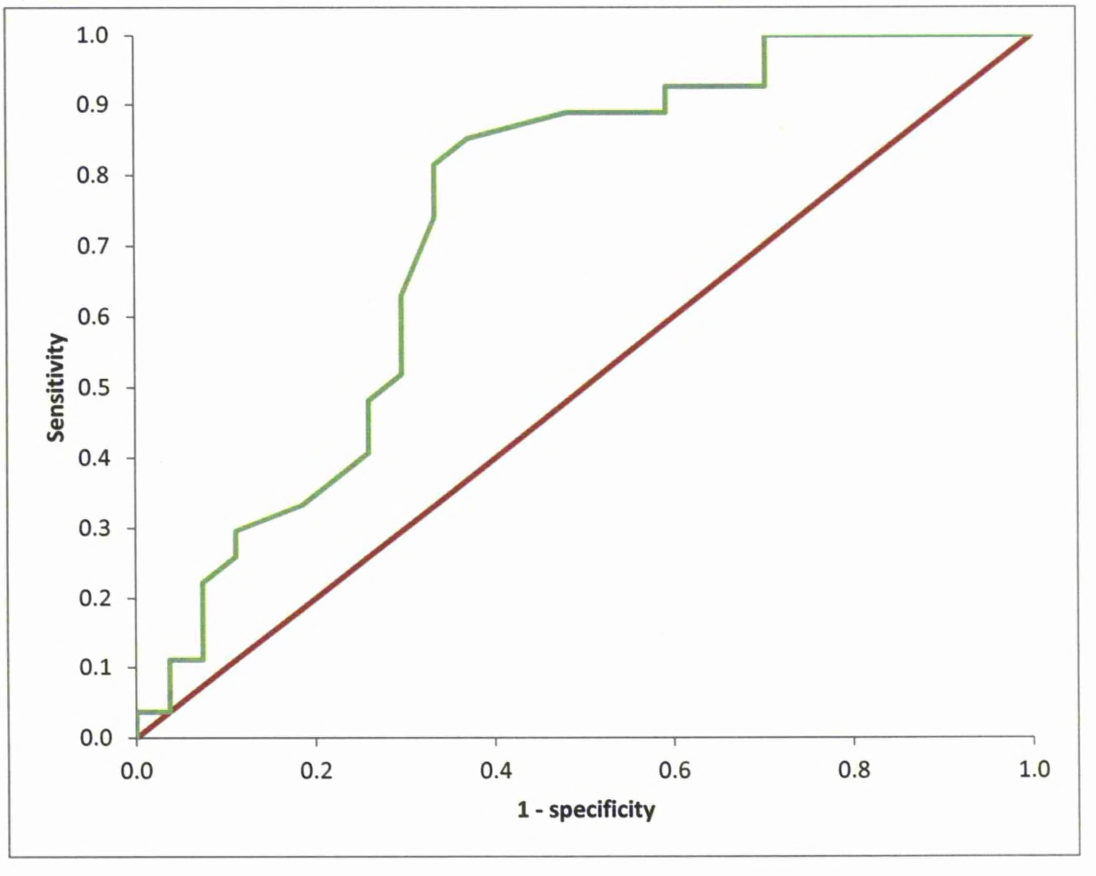
"Positive if Greater Than or Equal To" category is the first column in Table 19 which starts from 35 to end at 87. These numbers represent the BSQ values generated by the ROC curve software. The importance of those values is that it allows us, to locate the cut-off value for the fixed bridge, above which it is for certain the fixed bridge is stable and cemented, or below which it is unstable or moving and may need close observation in the future.

From the Table 19 the cross value to the highest sensitivity plus specificity column is considered to be a cut-off point which in the present study (in red colour) is 67.

The below figure is a moderate test accuracy according to Griener *et al.,* (2000).

Figure 32 ROC curve 100% bone support

ROC curve 100% bone support



AUC	0.735
Standard error	0.07

95% CI	0.597	0.872

5.6.6 ROC curve for 50% bone support fixed bridge

In the present study, another part of the research measured BSQ values on models having 50% simulated bone support. The steps in producing models with reduced bone support have been explained in details in the methodology chapters. The same procedure of making models with 100% bone support was followed in order to ensure the reliability and repeatability of the method, except for the amount of base material placed at the analogues.

Table 19 again shows sensitivity, specificity, and 1-specificity (false negative ratio). "Positive if Greater Than or Equal To" category in the Roc curve for 50% bone support table shows that the data starts from 40 to end at 86. From the Table 19 the cross value to the highest sensitivity plus specificity is 60 and it is considered to be a cut-off point of the present study.

Table 20

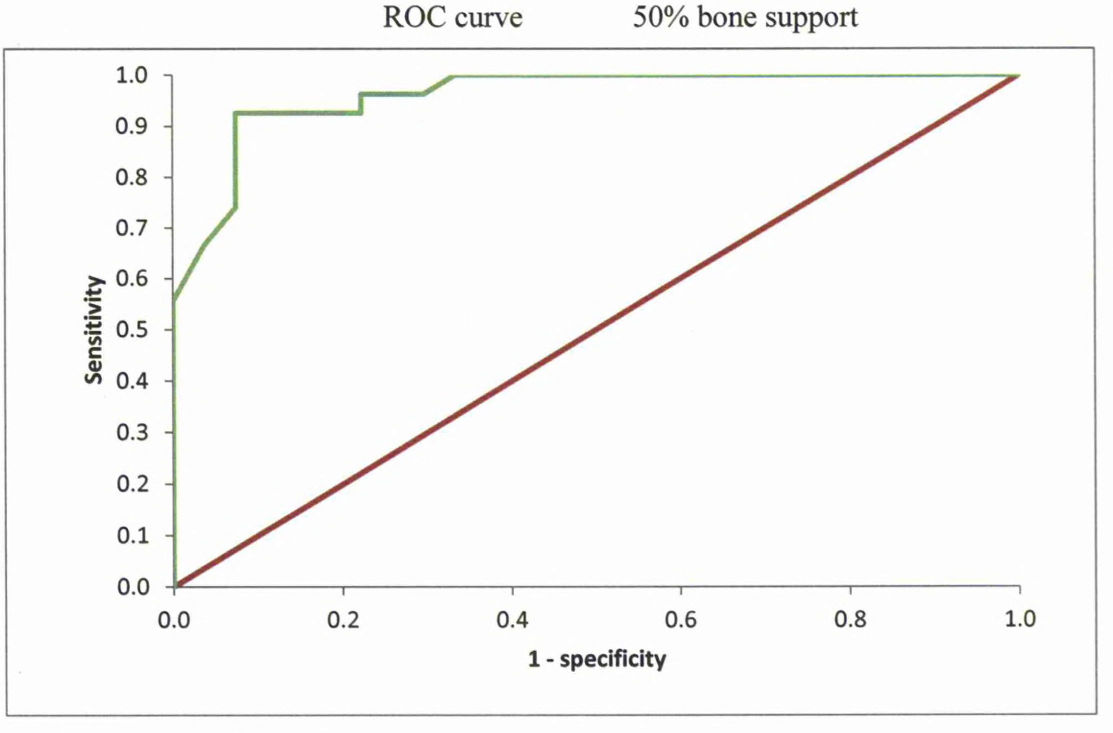
Coordinates of the ROC Curve for 50% bone support

Test Result Variable(s):premolar BSQ

Positive if Greater Than or Equal To	Sensitivity	Specificity	1 - Specificity	Sensitivity + Specificity
40.0000	1.000	.000	1.0	1.000
41.5000	1.000	.037	1.0	1.037
42.5000	1.000	.185	0.8	1.185
43.5000	1.000	.296	0.7	1.296
44.5000	1.000	.370	0.6	1.370
45.5000	1.000	.481	0.5	1.481
47.0000	1.000	.519	0.5	1.519
48.5000	1.000	.630	0.4	1.630
50.0000	1.000	.667	0.3	1.667
51.5000	.963	.704	0.3	1.667
52.5000	.963	.778	0.2	1.741
54.0000	.926	.778	0.2	1.704
56.5000	.926	.815	0.2	1.741
59.0000	.926	.889	0.1	1.815
60.5000	.926	.926	0.1	**1.852**
61.5000	.889	.926	0.1	1.815
62.5000	.852	.926	0.1	1.778
63.5000	.815	.926	0.1	1.741
64.5000	.741	.926	0.1	1.667
65.5000	.667	.963	0.0	1.630
66.5000	.556	1.000	0.0	1.556
67.5000	.481	1.000	0.0	1.481
68.5000	.407	1.000	0.0	1.407
69.5000	.370	1.000	0.0	1.370
71.0000	.259	1.000	0.0	1.259

72.5000	.222	1.000	0.0	1.222
74.5000	.148	1.000	0.0	1.148
76.5000	.111	1.000	0.0	1.111
80.5000	.074	1.000	0.0	1.074
84.5000	.037	1.000	0.0	1.037
86.0000	.000	1.000	0.0	1.000

Figure 33 ROC curve 50% bone support



AUC	0.96	
Standard error	0.023	
95% CI	0.904	1

The ROC curve shows (Figure 38), sensitivity and 1-specificity. Sensitivity is plotted in the Y axis starts from 0.6 and 1-specificity on the X axis. The data plots a line from the low far left point (0.6) to the far right uppermost point. The area between the curve and the line is the area under curve (AUC).

The results of ROC curve in the present study showed that the AUC was 0.96, and this is high test accuracy according to Greiner *et al.,* (2000).

5.6.8 Discussion of statistical results

5.6.8.1 Analysis of Variance (ANOVA)

Parametric statistical tests are based on estimates of the two population parameters, the mean and standard deviation and assume that they are of normal distribution. However, if the populations of the observations are not normally distributed, parametric methods become unreliable because the mean and standard deviation no longer describe the population. In these circumstances nonparametric tests may be used. When the observations are drawn from populations that are normally distributed, nonparametric methods are not only more reliable but more powerful than parametric methods (Stanton 1997).

If data are not normally distributed then we cannot use parametric tests ANOVA is a parametric technique as it assumes normality. A non-parametric equivalent of ANOVA is the Kruskal-Wallis test which can compare two or more groups of non-normally distributed data.

5.6.8.2 Validity and reliability

Before introduction of a new test in clinical practice, its sensitivity and specificity are usually determined as validity measures, where, the test results of diagnosed patients are compared to those of healthy people. In such populations absence of disease often does not mean that these people are healthy. The validity can be defined as a measure of relevance and addresses the appropriateness of the study. Reliability, however, measures how repeatable measures are, and it measures the stability of a study. Validity and reliability are therefore important in investigations. If a measurement is repeatable then we should get the same result or value when we measure the same thing twice or more. Reliability measures give a quantitative value for repeatability. It may be used to assess how repeatable a machine or instrument is. In the current study, it can be seen that the Osstell technique (using RFA) is highly reproducible between two investigators. It is likely that this was because the fixed bridges were identically made on the same duplicated stone model.

5.6.8.3 Sensitivity and Specificity

The diagnostic power of a test is expressed by its sensitivity and specificity of a positive or negative test result. Diagnosis of movement of fixed bridge by using Osstell apparatus is a new area for research, the procedure itself might be a reliable in detecting a stable fixed bridge rather than detecting the movement of fixed bridge. It may be very sensitive in that no uncemented/moving bridges are missed, but at the same time, it is not specific at all in that all fixed bridges are stable or cemented. There are four scenarios in this issue;

1. True positive decision, the bridge is uncemented or moving and has been detected that they do.
2. True negative decision, the bridge is stable (no movement) and we state this correctly.
3. False positive decision, the bridge is stable and we state that it does move.
4. False negative decision, the bridge is uncemented or moving and we state it does not.

Sensitivity is a measure of detection of abnormal cases, and, Specificity is a measure of detection of normal cases. In the current study, sensitivity is a measure of uncemented and mobile bridges where as the specificity is a measure of stable and cemented bridges.

Specificity is inversely related to sensitivity and both are used in ROC. If any decision is made where you are not certain about it, ROC can be use to find the agreement in the result. In this context, Sensitivity (Se) can be defined in the present research as the proportion of all uncemented fixed bridges that are correctly identified. It measures how well we identify those moving bridges. A true positive means that, in those bridges, we got it right and a false negative has occurred when we got it wrong. However, Specificity (Sp) is defined as the proportion of all stable or cemented fixed bridges that are correctly identified. It measures how well we perform in identifying those stable (i.e. cemented) fixed bridges. Specificity is the same as the true negative ratio so using false negative ratio is the same as using 1-specificty.

5.6.8.4 Receiver operating characteristic (ROC) curve

ROC is the term applied to the analysis and measurement of sensitivity and specificity at many thresholds (cut-off value). ROC analysis assesses "the diagnostic performance of the system in terms of Se and 1-Sp for each possible cut-off value of the test where, Se and Sp are a function of the selected cut-off value" (Greiner *et al.,* 2000).

If we cannot be 100% sure of what the decision is, it is important to get the diagnosis right and to understand that making a false positive diagnosis (where the bridge is stable and we state that it is moving). There is a potential biological penalty for a false positive diagnosis, but it may be less harmful in comparison to a false negative diagnosis (where the bridge is uncemented and we state that it is not). Thus in this case it is better to accept a poor specificity in order to ensure a very high sensitivity.

The actual benefit from a true positive diagnosis in the present research work is that the potential risk or the serious consequences of an uncemented fixed bridge mean that it can be treated in good time, and hopefully help to save the abutment tooth/teeth. The benefit from a false positive diagnosis, where the bridge is stable and we state it is not, is that any the bridge can be reviewed in future and any future cement failure loss could be diagnosed at an earlier stage.

5.6.8.5 The cut-off point for 100% and 50% bone support fixed bridges

There is a cut-off point in setting the threshold level and this is to allocate confidence levels to the decisions such as;

1. Very confident that the fixed bridge is uncemented.
2. Quite confident that the fixed bridge is uncemented.
3. Unsure if the fixed bridge is stable or not.
4. Quite confident that the fixed bridge is stable or cemented.
5. Very confident that the fixed bridge is stable.

For both continuous (data that require decimal places or fractions to report; measurements can take any value. Examples: lengths, areas, volumes, etc.) in addition, ordinal (data uneven but have ordering; for example, the position in a race, where first, second, third, etc. The numbers show position but not the size of the intervals between first and second etc.) measurements a threshold or cut-off value is required to categorize a test result as positive (abnormal) or negative (normal). Cut-off values are required in test evaluation studies for calculation of sensitivity (Se) and specificity (Sp) and also for clinical decision making (Gardner and Greiner 2006).

The cut-off point from the present study was found to be BSQ at 67 (in 100% bone support) and 60 (in 50% bone support), whereby any respective BSQ value less than 67 or 60 would lead us to consider a positive diagnosis (i.e. the bridge is uncemented or moving) and reject the null hypothesis, where only "very confident" or "quite confident" is set at the threshold to be considered a positive diagnosis. Thus it means we should have fewer false positives (where the bridge is stable but we state it is not) but more false negative diagnoses (where the bridge is uncemented and we state it is not).

Initial implant stability obtained after implant insertion is an important factor for the prognosis of the implant, and secondary stability may confirm a successful osseointegration and could demonstrate stability of the implant. Ramakrishna and Sanjna (2007) reported, in their *in vivo* study, that implants with higher primary stability ISQ >65 should be regarded as optimal and could maintain their stability with time, while implants with a lower primary stability of ISQ 50 may or may not increase in ISQ value with time and this value appears to be seen in less dense bone quality. They stated that a cut-off value below ISQ 45 should be considered as an early warning sign, which is similar to values in the current study, where it was found a BSQ value to be 67 in 100% bone support and 60 in 50% bone support. This means that any fixed bridge that has BSQ <67 or <60 should be considered as warranting further investigation and perform a thorough clinical examination including radiography.

5.6.8.6 Area under ROC curves (AUC).

The main interpretations of the AUC are; first, it is the probability that "the test results show a randomly selected diseased subject has a higher test value than a randomly selected non-diseased one" (Hanley and McNeil 1982). In the current study, the interpretation of the result in 100% of bone support is that 73.5% of the time a randomly selected uncemented fixed bridge group has a higher chance to be picked up than from the one of stable or cemented bridge.

Second, the AUC can be interpreted as the average of sensitivity (Se), averaged of the false positive fractions between 0 and 1 (Pope 2003).

ROC curves (AUC) may be shown as percentages from 0% to 100% or as numbers 0 to 1. Data that will give a point on the graph that is close to zero for the false positive rate and close to 1 (or 100) for the true positive rate are "ideal" or more accurate. This means that, ideally, a point should lie in the top left hand corner of the graph and as far from the slope as possible.

The area under the ROC curve in the "100% bone support" was calculated to be 0.735 which presents a moderate accuracy of the resonance frequency test. The interpretation of this result is that 73.5% of the time a randomly selected uncemented fixed bridge group has a higher chance to be picked up than from the one of stable or cemented bridge. However, the AUC for "50% bone support" should be considered to be of high accuracy as it is 0.96. This means that 0.96 point lies in the top left hand corner of the graph and indicates a "very confident" or "quite confident" test threshold.

The Statistical Package of Social Science (SPSS) built-in features can be used to perform an ROC analysis, using the "Graphs" pull-down menu. Use of the ROC curve has several advantages such as; it allows assessing a classification at several sensitivity and specificity levels. In addition, sensitivity and specificity are calculated separately. Sensitivity considers those that have the condition, while specificity considers only those that do not. Furthermore, two or more ROC plots can be compared visually. A plot lying above and to the left of another plot shows greater accuracy.

However, it has several problems such as; two ROC curves can have the same area but have very different characteristics, i.e. one plot may have much better specificity at low sensitivity and the other better specificity at higher sensitivity. Moreover, comparison of ROC plots statistically can be difficult, especially where two tests are performed on the same patient.

In conclusion, ROC analysis visualises the cut-off need of diagnostic tests and provides an estimate of the accuracy that is independent of specific cut-off value and prevalence. It allows a comparison between different diagnostic tests.

5.7 Discussion of the main study results.

The main aim of this thesis was to investigate the viability of electromagnetic resonance frequency analysis (Osstell apparatus) as a novel method to measure the fixed bridge stability *in-vitro*.

There has been discussion in the literature of the use of a non-invasive method (RFA) to measure the stability of dental implant and viability. This technique relies upon detecting implant movement at time of placement (primary stability), during various stages of osseointegration, and as a follow-up later during function. However, The RFA method has not been used previously to measure fixed bridge stability in dental laboratories or dental clinics, allowing this research to be presented as novel work.

5.7.1 Introduction

When planning fixed prostheses for missing tooth/teeth, options include fixed bridges supported either by tooth or dental implants. These treatment decisions should be based on well documented reviews and evidence-based dentistry and should be based on the highest level of evidence available (Egger *et al.,* 2001). Decisions should also consider various biomechanical, biological and as well as technical risks while treatment planning. A series of systematic reviews based on certain criteria and utilisation of available information on survival and success rates and the incidence of biological and technical complications of conventional fixed prostheses construction have been reported in the dental literature (Pjetursson *et al.,* 2004; Lang *et al.,* 2004).

For conventional tooth supported fixed prostheses, the most frequent complications are mechanical or technical such as loss of retention, fracture of veneer materials. Biological complications include caries and loss of pulp vitality.

Pjetursson *et al.,* (2007) reported the estimated 5 year survival of conventional tooth supported prostheses of 93.8% and 95.2% for implant supported prostheses. In addition, after 10 years of function, the estimated survival decreased to 89% for conventional fixed prostheses and 86.7% for implant supported prostheses.

Although the success or failure of conventional fixed bridges is affected by a number of factors, the present study focuses on the loss of retention and its sequels of complications that effect the long-term survival of fixed prostheses, by using a novel application of chair side resonance frequency analysis (Osstell Mentor) in the fixed prosthodontic field.

The longevity of success fixed bridge is often assessed by a periodic examination (usually – 6-monthly to yearly) or when a patient complains of symptoms. This is often however, in the late stages of bridge failure.

There are a limited number of ways of detecting bridge failure such as:

1. Clinically: on intra-oral examination, bubbles of saliva may be detected by pulling/pushing alternately on each retainer of a bridge when complete cement failure has occurred. In addition, the patient may notice a bad odour or taste due to bacterial growth under the retainer, which can lead, if not detected in time, to destroy the abutment tooth structure by caries. In these cases possible recementation of the fixed bridge is reduced or impossible. Furthermore, there may (rarely) be sensitivity to hot or cold with early failure, or severe, spontaneous pain with late (and unrestorable) failure.

2. Radiographically: caries may be detected radiographically at the margin of bridge retainer of the abutment tooth. However, this approach has its limitations. Sunden *et al.*, (1995) emphasised the need for high quality radiographs often for accurate diagnosis in dentistry.

Therefore, there is clearly a need for an objective method to measure fixed bridge stability which may enable diagnosis of the early stages of movement of these bridges.

The present method was able to answer the research question with certainty that is resonance frequency analysis (RFA) is an appropriate method of measuring a bridge stability *in-vitro.* RFA was applied to metal fixed bridges on models with simulated 100% and 50% bone support using a reproducible method. The investigation demonstrated how recording RFA values from one direction (buccal) using the Smartpeg and Osstell probe allows detection of movement on uncemented (considered failed) fixed bridges *in-vitro.* It demonstrated also, how RFA may provide a useful method of predicting fixed bridge movements in clinical situations by assessing laboratory models, accepting the limitations of this study and the ability, within the laboratory to control various factors that may affect the RFA readings. It was possible, therefore, to reject the null hypothesis of this study and demonstrate that the use of RFA has the potential to differentiate between uncemented (moving) fixed bridges and cemented (stable) fixed bridges *in-vitro*.

5.7.2 The construction of "periodontal models"

The periodontal models consisted of acrylic analogue teeth as abutments, and an elastomeric material to simulate the natural periodontal ligament, being based in dental stone material to act as the bone. The simulated periodontal membrane was constructed by dipping the acrylic root once into the polyvinyl-siloxane elastomeric impression material and this was allowed to set. The normal thickness of the periodontal ligament ranges in width from 0.15 to 0.38 mm (Nanci 2003). In this present study it was measured, using callipers, as ranging from 0.11 to 0.14 mm. The principle investigator ensured that the periodontal-like material was similar on all root surfaces, but the study methodology did not allow the investigator to exhibit the same width on each analogue. Hence, there may be some area where the thickness was very thin, effectively locking the acrylic abutment independently (mimicking ankylosis), and this could have affected the BSQ readings that were obtained. After coating the acrylic teeth with the elastomeric material they were repositioned in the mould index and dental stone poured to the mould in order to produce the finished models. The principle investigator made every effort to ensure the dental stone did not come into contact with the coronal elements of the tooth by covering above the finish line (CEJ) of the acrylic teeth by the elastomeric material. This was to prevent any root locking (ankylosis) and to allow the roots with the periodontal-ligament like material to move independently for consistent BSQ readings.

5.7.4 Sample size

When planning a study we need to choose an appropriate sample size. Proper statistical results require careful planning. They must be selected from an appropriate population, be randomised and reliable instruments be used to obtain measurements and must be of adequate sample size.

In the present study, the sample size was based on our pilot study results and its conclusions, and after statistical advice from the Departmental Lecturer in Dental Statistics (Dr G Burnside). The data analysis will consider sensitivity and specificity of the test using the Receiver Operating Characteristic (ROC) curve. The area under the ROC curve (AUC) can be used as a measure of the quality of the diagnostic test. If our test has an AUC of 0.9, a sample size of

25 cases and 25 controls will be sufficient to estimate the AUC with a 95% confidence interval of +/- 0.09. The sample was calculated as 50.

A proper sample size calculation is very important as an inadequately sized study can be waste of materials leading to no useful results; while an over-sized study uses more materials than necessary. In clinical investigations both undersized and oversized studies could expose the subjects to harmful treatments without justification.

In the current investigations, nonparametric statistical analysis was employed. One-way analysis of variance could have been used if the population means were equal, but if, as in the data obtained, the samples are not normally distributed a nonparametric test alternative to one-way analysis may be used. Examples of tests that may be used are: Mann-Whitney (to compare two unpaired groups), Wilcoxon matched pairs (to compare two matched groups) and Kruskal Wallis (capable of testing two or more unpaired groups).

5.7.4 Convergence angle of the tooth preparation on periodontal models

It is well known that in fixed prosthodontics, the smaller the convergence angle between the opposite surfaces of the preparation; the better will be the retention (Jorgensen, 1955). Parallelism of axial walls is important in retention of dental restorations (El-brashi 1969). Early work by Tylman (1950), to find out the relationship between parallel axial walls, concluded that a slight divergence of 2 to 5 degree from parallelism is required for proper retention and resistance. The degree of convergence of axial walls were also evaluated by Lewis and Owen (1959), who also reported that the retention decreased as the angle of axial walls increases.

The findings stated by Jorgensen (1955), where the optimal convergence angle has to be below 20°, coincides with the convergence angles in the present study. However, 4 specimens showed greater convergence than 20°. These models were excluded from the study and replaced by new construction of four models. Several studies (Rosenstiel 1957, Kaufman *et al.,* 1961, Kishimoto *et al.,* 1983) reflect the importance of the convergence angles and prepared tooth surface to influence the retention and resistance of the crowns and bridges.

Kaufman *et al.,* (1961) mentioned the various factors that affect retention of the prepared tooth, such as the height and the surface area of the prepared surface and the degree of convergence of the opposing walls of the preparation. They noted that the 1° convergence die exhibited 10 times the retention of the 20° die. Several studies were focused on the use of geometric features in preparation for cast restorations to resist tipping and removal forces, and analysis of mechanical relationship between degree of taper, preparation length and surface area (Smyd 1944; Rosenstiel 1957; Potts *et al.*, 2004).

Based on these studies, the convergence angles used in the current investigation were standardised to; a) evaluate the retention form in order to ensure the passive fit of metal bridges on all models and b) at the same time also to construct models with maximum retention when these bridges were cemented.

A number of possible explanations for the variation in convergence angles exist. One is the shrinkage of the heat cure acrylic resin. Because of this the principle investigator ensured that all models had an acceptable convergence angle, and were distributed evenly between the two groups so that the BSQ readings were not skewed and to ensure the consistency of the method.

The investigator constructed four new models with a more desirable convergence angle (<20°). The sample size of 50 specimens to measure BSQ value was therefore maintained. The passive fit of the fixed bridge on the model was ensured to be equal in all bridge work. This is done with help of digital pressure and scale (to measure how many kilograms were required to pull-off the uncemented passive fit fixed bridge in an occlusal direction from the model).

5.7.5 BSQ values of uncemented-uncemented fixed-fixed bridges (negative control) on 100% bone support periodontal models.

The mean BSQ values for uncemented molar abutments in the negative control group were 22 – 57, with an average of 39. The uncemented premolar abutments in the negative control group were 28 - 56 with an average BSQ reading of 42. This average reading was similar to the results obtained in the pilot study. It suggests that, when there is no cement to fix the premolar abutment, there is more movement of this bridge. If this was applied to the clinical situation, it would indicate failure was occurring, so if the Osstell Mentor could detect this slight bridge movement at an early stage, the abutment tooth would have a better prognosis and appropriate treatment will be commenced.

The Table 14 shows mean BSQ values of molar abutments, where the premolar was uncemented (C-F) were 28-56 with molar average BSQ reading of 42. Despite the molars having a large surface area and long clinical crown (both increasing the retention of bridge) they showed lower BSQ readings in comparison to the control (group 1, C-C) group. This decrease in BSQ values on the molars in test group (group 2, C-F) was thought to be because as the premolars were uncemented and molars cemented, the bridges can produce some movement due to resiliency of the elastomeric impression material used to mimic the periodontal ligament.

Sennerby and Meredith (2008) reported the performance of different implant types; these implants approach a similar level of stability, for Branemark implants type ISQ of 65-75, for Straumann type to be ISQ of 65, so, implants of ISQ ≥65 should be considered as a stable, optimal implant and these require minimal follow-up in future. On the other hand, less stable implants with ISQ<49 might need more follow-up and they are at higher risk (Glauser *et al.*, 2004; Sennerby & Meredith, 2008).

5.7.6 BSQ values for positive control (group 1, C-C) and test group (group 2, C-F) of 100% bone support

The specimens were not randomly allocated but were stratified because of the time taken to produce the 50 models (in both 100% and 50% bone support forms) and the effect that a learning curve may have exerted upon the results. These models were divided using blind, stratified, randomisation by a second investigator into two groups based on the first and middle and late models (made by the principle investigator) to produce consistent and reproducible periodontal models.

Despite efforts to standardise all method procedures, differences in convergence angles were observed and randomization may have distributed these unequally which may have skewed the results. A second investigator performed the cementation to ensure subsequent blind assessment by second investigator into two groups; control group (group1, C-C) and test group (group 2, C-F). The cementation pressure amounted to an 8kg weight used to apply seating pressure to the bridge and maintained for 10 min. The 8kg weight came as a result of measuring thumb pressure on a balance and averaging these results. The principle investigator applied pressure via his thumb, the equivalent reading in kilograms was noted, then the same procedure was repeated by the second investigator and 8kg was the average of both readings. An 8 kg weight was subsequently used as seating pressure on metal fixed-fixed bridge for about 1 minute. This procedure was broadly similar to 4 kg of cementation seating pressure used previously (Jorgensen 1955). All excess cement was removed by dental instruments after it reached initial set according to clinical practise.

All 50 models (divided on controlled, blind, and stratified randomisation) were placed and sealed inside polythene bags (each bag containing one model) which allowed the luting cement to set for 24 hrs. These bags were used to maintain a constant humidity and prevent the lute cement from over drying as this may affect the obtained BSQs.

All BSQ readings were taken 7 days following cementation with the principle investigator recording these "blind" to the grouping. The BSQ recording after 7 days allowed full maturation of the luting cement but was also due, in part, to the Osstell Mentor experiencing problems in retaining charge preventing all records being obtained at 24h.

The BSQ readings were taken from the buccal direction (based on results from the pilot study) for all models. As pilot studies demonstrated that there were no statistically significant differences between buccal, occlusal, palatal, mesial and distal directions; buccal recordings were used to take the BSQ readings, it also, because this surface is easily accessible in the patient mouth. This finding also confirms the result reported by Veltri *et al.,* (2007) where they concluded that there was no significant difference resulted in implants between the bucco-palatal position/direction and between the mesio-distal directions.

5.7.7 Resonance frequency analysis (FRA) and BSQ values

Implant stability can be defined as the absence of clinical mobility which is an important factor for successful clinical outcomes of dental implant. However, a clinically stable dental implant may exhibits micro-scale mobility if a lateral load is applied to integrated implant. This will displace the implant but it will return to its original position as soon as the load is removed (Sennerby and Meredith 2008).

According to Sennerby and Meredith (2008), resonance frequency analysis applies a bending load to assess the stability of implant, which often mimics the lateral load in patient's mouth.

A fixed bridge is stable and firmly fixed on to the abutment tooth with the help of various mechanical features of retention; resistance form and lute cement materials. Failure in one of these could lead to movement or instability of a bridge which subsequently may be failing.

The resonance frequency analysis technique in the present study assessed bridge stability in simulations of 100% and 50% bone support, by applying an external impulse from the probe to a Smartpeg magnetic head, which was attached (by composite) to the metal framework of the fixed bridge. There were several attempts to affix the Smartpeg to the metal framework, such as; the first attempt was to solder the Smartpeg with help of soldering machine into the metal frame work of the bridge but this was not possible due to the Smartpeg material being incompatible with soldering. A second attempt was to make a matching screw hole in the bridge metal frame and thread the Smartpeg into this hole. However, this was technically very complex and could not be used clinically if bridges had not been constructed with a screw hole in place.

The Smartpeg vibrates into two directions, one direction that gives the highest resonance frequency and the second gives the lower resonance frequency. The excitation signal was displayed on Osstell Mentor as a parameter which we have termed bridge quotient stability (BSQ) values.

The fixation of Smartpeg was one of the most important variables to control in the present study, using the composite resin to affix it against the metal framework of the bridge at embrasure area. The reference point for placing of Smartpeg in the same position by the principle investigator every time was that the full length of the Smartpeg serration had to be embedded in composite resin. The length and the density of the Smartpeg are very important for the calibration of the Osstell instrument as anything affecting the length may alter the resonance frequency of the Smartpeg.

5.7.9 BSQ values on simulated 100% bone support models

The Osstell Mentor demonstrated higher bridge stability (100% bone support) in the positive control group where the bridges were cemented by zinc phosphate on both retainers. The average BSQ value was 72, which indicates that the bridge is stable; strongly supporting the view that cemented bridges can be measured objectively. Based on resonance frequency analysis measurements of fixed bridge stability, any BSQ value of fixed bridge above 67 could be considered to be stable (i.e. cemented).

Additionally it can be stated that the positive control group exhibited higher BSQ values both on molar and premolar. This result confirms that the bridges were stable, cemented and fixed in place and it can be stated that the resonance frequency analysis device was able to measure fixed bridge stability *in-vitro*. This therefore answered the research question whether it was possible to use RFA to detect fixed bridge stability by measuring the differences between uncemented and cemented fixed bridges in vitro. The null hypothesis of the methodology can be rejected and there it was possible to detect statistically significant differences between uncemented and cemented fixed bridges on "periodontal" stone models.

However, the test group showed lower BSQ values in comparison to the control group, which could be explained by that the bridges were moving due to no cement to make them fixed to the anterior abutment. These were then tending to move as though they were extended cantilever bridges.

Lekholm and Zarb (1985) measured the relationship between bone quality and primary implant stability, and showed a low implant stability quotient (ISQ) in less dense bone and their data also indicated that the stiffness of the implant-bone interface is high in dense bone. The same finding was reported by Boronat *et al.*, (2008), where they found that higher ISQ values for implants placed in dense compact bone. O'Sullivan *et al.*, (2000) in a cadaver study, compared insertion torque and bone qualities and reported that high ISQ values for different bone types except bone type IV. This tends to confirm that low movement results in high ISQ values and supports the current findings, albeit measuring a different system (i.e. fixed bridge).

An interesting result found in the present study was that the average BSQ value on the molar abutment dropped from 72 in the control group to 66 in the test group. The likely reason behind this is that the non cemented premolar retainer allowed slightly increased movement of the molar retainer via the bridge

5.7.10 BSQ values for control (group 1, C-C) and test group (group 2, C-F) of 50% bone support.

The analysis of the present study showed that the RF technique using Osstell equipment is reliable and sensitive to identify the uncemented/unstable fixed bridges. Glauser *et al.*, (2004) used Branemark implant system, concluded that failing implants showed a continuous decrease in ISQ values after two months, to indicate that these are at risk of failure in the future. The result of the present *in-vitro* study showed a significant decrease ($p<0.05$) in BSQ values for 50% bone support bridges in the test group (group 1, C-F).

Lachmann *et al.*, (2006) performed an *in-vitro* study to compare RF analyser and the Periotest device on dental implants. They stated that both devices were suitable to detect the decrease in implant stability and used this as an indication of bone loss *in-vitro,* and the RF device may be more sensitive to detect bone loss earlier, in comparison to the other device. The results of the present study show that cemented fixed bridges of 100% bone support demonstrated a higher mean BSQ value (67) compared to the BSQ value for 50% bone support fixed bridges (60).

5.7.11 The survival of fixed-fixed bridge using RFA

A main aim of any restorative procedure in dentistry is to avoid failure. The same principle applies to implants as to fixed prostheses and, in both of these cases unexpected mobility is an indicator of failure.

It is clear that, from the study by Glauser *et al.*, (2004), the lower the implant stability quotient (ISQ) value after 1 month of loading, the higher the risk of failure in future. The lower BSQ value in the current investigation also indicated that the bridge is "at risk" and clinically this could transfer as a recommendation that low BSQ value bridges would require close observation re-examination in 3-6 months time.

In an implant study by Nedir *et al.*, (2004) that compared immediate loaded implants with implants loaded after 3 months, they concluded that implant stability could be determined with an ISQ of more than 47. However, it was noted that the resonance frequency analysis technique could not identify all mobile implants. The possible cause of not detecting some mobile implants may be because of resonance frequency technique measures stability as a function of stiffness, where the mobile implants show low stiffness, which prevents the resonance system from identifying the first resonance frequency. Therefore, it might record a false high resonance frequency quotient value in relation to the second resonance frequency (Meredith 1998). This explanation may account for some observations in the present study that the resonance frequency analysis technique could not identify some uncemented fixed bridges. To date there are no other studies that document the role of resonance frequency technique to be reliable method in identifying uncemented or mobile fixed bridge either *in-vitro* or *in-vivo* studies.

The resonance frequency analysis technique can be useful in follow-up observation of implants, and it has been found to be useful for assessing immediate loading implants during different treatment stages. In addition, it can give relevant information about the state of the implant-bone interface. In parallel, in the current investigation, it appears to indicate with certainty that bridges with high BSQ values are successful bridges and are stable, whilst low or decreased BSQ values may be considered as a sign of failure and the bridge is at risk in future. However, more *in-vitro* and *in-vivo* studies are needed to determine the accuracy of this technique and then draw up recommendations for the use of the resonance frequency analysis technique to detect and record mobility of bridges.

5.7.12 Universal Testing Machine (UTM)

Fixed bridge retainer displacement often occurs because features of the tooth preparation do not oppose the forces directed against the restorations. This is an important consideration while configuring the tooth preparation.

Early studies of designs of tooth preparation were based on preparation features that could geometrically resist tipping and removal forces (Reisbick and Shillingburg, 1975). Other studies have focused on the relationship between degrees of taper (convergence angle), preparation surface area, preparation length and the force that is necessary to remove cemented retainers (Jorgensen 1955; Kaufman *et al.,* 1961).

The bridges were all cemented using zinc phosphate cement. Zinc phosphate cement was mixed for 60 seconds on a room temperature glass slab, and each bridge was cemented with 8 Kg seating pressure for 10 minutes which is broadly similar to the values reported by Jorgensen (1960) where he used 11.5 pounds seating pressure for 10 minutes to seat bridges.

As with other cements, zinc phosphate cement becomes dry and brittle in the absence of moisture and in warm room temperatures. For these reasons the models were left in a sealed polythene bag to ensure a more constant humidity for all cemented bridges before testing.

The amount of tensile force (using the UTM) needed to produce debonding varied amongst specimens. This appears to have been dependent upon the number of abutments cemented. Most of specimens were failed by molar debonding at high loads. These were from group 1 (cemented-cemented, C-C) where both abutments were cemented. There was no correlation between these and the convergence angle on the abutments. However, most of the test group (group 2, C-F) specimens failed by extraction of the molar (the only retainer cemented) at loads below 50N. This mode of failure might have been because of the presence of the periodontal-like membrane that allowed extraction of one abutment and subsequent tilting with a torqeuing, rather than a tensile effect. This may have been remedied by using an acrylic rather than stone base but this was not able to be assessed in the current study.

Given the un-predictable nature of the mode of failure of models subject to this testing method it was considered that the data obtained by UTM was too unreliable to analyse and hence the decision was made that this method was not suitable to be used as a comparison to the RFA data.

5.8 Limitations of the study

All fixed-fixed bridges were constructed in the posterior region using the first premolar and first molar as abutments. However, fixed-fixed bridges are also used in the anterior region. They can improve the aesthetics and functions of patients but we selected posteriors because it was considered that it is more difficult to diagnose loose retainers or cement failure here.

A periodontal ligament-like structure was made from elastomeric impression material (Polyvinyl-siloxane) to resemble the natural periodontal ligament. However, in nature it is composed of collagen fibres and blood vessels, which in thin section, adhere to the cementum of the root surface. This functions as a viscoelastic cushion to absorb/accommodate the pressure on the tooth while functioning.

Stone models were used but were not always able to withstand the load from the Universal Testing machine (UTM). Using acrylic models could improve the strength of these models to perform the UTM test to assess the retention of the bridges alone, rather than cohesive strength of the base and the retention of the tooth analogues within this.

There may have been variation in the Smartpeg length and the amount of composite resin placed to affix it to the metal work. However, a standardised material and procedure was used as well as using only one investigator to reduce these variables.

The 50% bone support models were made by measuring the root length and dividing this by two to produce half of the root embedded in the stone. There were slight variations in this coverage, but only to a limited extent (± 5%).

The principal investigator ensured that the stone material did not touch the acrylic tooth as this would have affected its ability to move independently in the stone model. However, it was impossible to check that this had not occurred due to a defect below the visible surface.

An *in-vivo* study should now be carried to assess the transferability of the results from the *in-vitro* laboratory work.

5.9 Conclusions

- It has been shown that resonance frequency measurements are able to identify stable, cemented bridges in the present study.
- RFA may be used to monitor changes in the movements of fixed bridge over a period of time which may help to differentiate between successful fixed bridges and bridge failures and so we can reject the null hypothesis.
- The cut-off point from the present study was to be found at BSQ value of 67 in 100% bone support and 60 in 50% bone support. If BSQ values are less than 67 and 60 respectively then clinicians should consider a positive diagnosis and further investigation is warranted.
- Use of RFA showed high BSQ values in most (88%) of the positive control group and in some (45%) of test group models.

6 AREAS FOR FURTHER RESEARCH

- Use of analogue abutment teeth with curved roots might help in retention of the abutment into the cast and allow more representative use of tensile load to assess the mode of failure.

- Use of acrylic materials to construct acrylic bases instead of stone may also help to prevent fracture of these while testing by UTM.

- Anterior bridge design can be tested using modifying models and the same RFA equipment to assess the BSQ values obtained and the suitability of this technique to identify stable/failed anterior fixed bridges *in-vitro*.

- Modification of a Smartpeg design to allow reliable attachment onto bridge framework.

- With further development of the RFA technique it may be possible to identify the conditions which may affect bridge stability and thereby provide necessary treatment in good time.

- The Osstell manufacturing company has now lodged a patent application for a modified Smartpeg to allow this technique to be developed for clinical use (Figure 41).

Figure 42 Swedish Patent Application for modification of Smartpeg

PRV
PATENT- OCH REGISTRERINGSVERKET

UNDERRÄTTELSE OM PATENTANSÖKAN

Beslutsdatum 2011-08-12

Patentansökan nr 1001237-5

Callum Youngson
63 Thurstaston Road Heswall
CH60 6SA Wirral
Storbritannien

Sökande: Ostell AB

Ombud: Valea AB

Brevet sänds till: Anders Petersson, Nedergårdsgatan 5, 416 54 Göteborg. Callum Youngson, 63 Thurstaston Road Heswall, CH60 6SA Wirral, Storbritannien.

Underrättelse om patentansökan
Ovan angivna patentansökan har getts in till Patent- och registreringsverket. Sökanden har angett er som uppfinnare av den patentsökta uppfinningen.

Information regarding patent application
The above mentioned patent application has been filed with the Swedish Patent and Registration Office. You are indicated as the inventor in the application.

Marie Nilsson
Formaliahandläggare/Formality examiner
Tel växel/Phone: 08-782 25 00, direkt/direct 08-782 25 87

Box 5055, 102 42 Stockholm [Besökare: Valhallavägen 136]
Tfn: 08 - 782 25 00, Fax: 08 - 666 02 86, PlusGiro: 156 84 - 4, Bankgiro: 5050 - 0248
www.prv.se

J-16 (2011-07-01) 1 (1)

7 REFERENCES

Abbott PV. Incidence of root fracture and methods used for post removal. Int Endod J 2002; 35: 63-67.

Adams RD, Cawley P. Vibration techniques in non-destructive testing. Research techniques in Non-destruction Testing 1985; 8 :303-360.

Akatyev VA. Reasons for the premature removal of crown and bridge prosthesis. Stomata ologiia (Mosk) 1979; 58: 84-112 (English Abstract).

Albrektsson T, Linder L. A method for short- and long-term *in-vivo* study of the bone-implant interface. Clin Orthop Relat Res 1981; 159: 269-73.

Albrektsson T, Carina B, Johansson G, Sennerby L. Biological aspects of implants: Osseointegration. Periodontol 2000 1994; 4: 58-73.

Allen RK, Newton CW, Brown CE. A statistical analysis of surgical and nonsurgical endodontic retreatment cases. J Endod 1989; 15: 261-6.

Al-Shammary A. Treatment decisions in the aesthetic restoration of upper incisor teeth, 2000, MDentSci Dissertation, University of Leeds.

Altshul JH, Marshall G, Morgan LA, Baumgartner JC. Comparison of dentinal crack incidence and of post removal time resulting from post removal by ultrasonic or mechanical force. J Endod 1997; 23: 683–6.

Aparicio C. The use of Periotest value as the initial success criteria of an implant; 8 year report. Int J Periodont Rest Dent 1997; 17: 150-161.

Assif D, Bitenski A, Pilo R, Oren E. Effect of post design on resistance to fracture of endodontically treated teeth with complete crowns. J Prosthet Dent 1993; 69: 36-40.

Assif D, Aviv I, Himmel R. A Rapid dowel core construction technique. J Prosthet Dent 1989; 61: 16-7.

Baier RE, Glantz PO. Characterization of oral in vivo films formed on different types of solid surfaces. Acta Odontol Scand 1978; 36: 289-301.

Barrack G. Recent advances in etched cast restorations. J Prosthet Dent 1984; 52: 619-26.

Barrack G, Bretz WA. A long-term prospective study of the etched cast restoration. Int J Prosthodont 1993; 6: 428-434.

Bassi GS. An *in-vitro* study to assess the amount of dentine exposed during resin bonded bridge preparations on premolar teeth and an investigation of microleakage around resin bridge retainers and the effects of the application of a dentine bonding agent 2002, MDent.Sci Dissertation, University of Leeds.

Bassi GS, Youngson CC. An *in-vitro* study of dentin exposure during resin-bonded fixed partial denture preparation. Quintessence Int 2004 ;35: 541-548.

Bates JF, Stafford GD, Harrison A. Masticatory function-a review of the literature. III. Masticatory performance and efficiency. J Oral Rehabil 1976; 3: 57-67.

Berekally TL, Smales RJ. A retrospective clinical evaluation of resin-bonded bridges inserted at the Adelaide Dental Hospital. Aust Dent J 1993; 38: 85-96.

Bergenholtz G. Iatrogenic injury to the pulp in dental procedures: Aspects of pathogenesis, management and preventive measures. Int Dent J 1991; 41: 99-110.

Bergenholtz G, Cox CF, Loesche WJ, Syed SA. Bacterial leakage around dental restorations: its effect on the dental pulp. J Oral Pathol 1982; 11: 439-50.

Bergenholtz G, Nyman S. Endodontic complications following periodontal and prosthetic treatment of patients with advanced periodontal disease. J Periodontol 1984; 55: 63-8.

Bergman B, Olsson KA, Stenberg T. Dimensional stability of a rubber impression material. The effect of storage time prior to pouring of the stone die. Sven Tandlak Tidskr 1972; 65: 559-68.

Bischof M, Nedir R, Szmukler S, Bernard Jean-Pierre, Samson J. Implant stability measurement of delyed and immediately loaded implants during healing. A clinical resonance frequency study analysis study with sandblasted and etched ITI implants. Clin Oral Impl Res 2004; 15: 529-539.

Boronat A, Penarrocha M, Carrillo C, Marti E. Marginal bone loss in dental implants subjected to early loading (6 to 8 weeks postplacement) with a retrospective short-term follow-up. J Oral Maxillofacial Surg 2008; 66: 246-50.

Botelho MG, Dyson JE. Long-span, fixed-movable, resin-bonded fixed partial dentures: a retrospective, preliminary clinical investigation. Int J Prosthodont 2005; 18: 371-76.

Botelho MG, Leung KC, Ng H, Chan K. A retrospective clinical evaluation of two-unit cantilevered resin-bonded fixed partial dentures. J Am Dent Assoc 2006; 137: 783-88.

Botelho MG, Nor LC, Kwong HW, Kuen BS. Two unit cantilevered resin-bonded fixed partial dentures, a retrospective, preliminary clinical investigation. Int J Prosthodont 2000; 13: 25-28.

Botelho MG. Resin-bonded prostheses: The current state of development. Quintessence Int 1999; 30: 525-534.

Botelho MG. Design principles for cantilevered resin-bonded fixed partial dentures. Quintessence Int 2000; 31: 613-619.

Boyer DB, Williams VD, Thayer KE, Denehy GE, Diaz-Arnold AM. Analysis of debond rates of resin-bonded prostheses. J Dent Res 1993; 72 :1244-48.

Branemark PI, Hansson BO, Adell R, Breine U, Lindstrom J, Hallen O, Ohman A. Osseointegrated implants in the treatment of the edentulous jaw. Experience from a 10-year period. Scand J Plast Reconstr Surg (Suppl) 1977; 16: 1-132.

Branemark PI. Osseointegration and its experimental background. J Prosthet Dent 1983; 50: 399-410.

Branemark PI, Zarb GA, Albrektsson T, eds. Tissue integrated prostheses: osseointegration in clinical dentistry, 1985, 1-343. Chicago: Quintessence.

Brannstrom M, Nordenvall KJ. The effect of acid etching on enamel, dentin, and the inner surface of the resin restoration: a scanning electron microscopic investigation. J Dent Res 1977; 56: 917-23.

Brannstrom M. The effect of dentin desiccation and aspirated odontoblasts on the pulp. J Prosthet Dent 1968; 20: 165-71.

Briggs P, Dunne S, Bishop K. The single unit, single retainer, cantilever resin-bonded bridge. Br Dent J 1996; 181: 373-79.

Budtz-Jorgensen E, Isidor F. A 5 year longitudinal study of cantilevered fixed partial dentures compared with removable partial dentures n a geriatric population. J Prosthet Dent 1990; 64: 42-47.

Castrisos T, Abbott PV. A survey of methods used for post removal in specialist endodontic practice. Int Endodont J 2002; 35: 172-180.

Cawley P, Woolfery AM, Adams RD. Natural frequency measurements for production quality control of fibre composites. Composites 1985; 16: 23-27.

Chai J, Chu FC, Newsome PR, Chow TW. Retrospective survival analysis of 3-unit fixed-fixed and 2-unit cantilevered fixed partial dentures. J Oral Rehabil 2005; 32: 759-65.

Chang HK, Zidan O, Lee IK, Gomez-Marin O. Resin-bonded fixed partial dentures: a recall study. J Prosthet Dent 1991; 65: 778-81.

Cheung GS. A preliminary investigation into the longevity and causes of failure of single unit extracoronal restorations. J Dent 1991; 6: 279-284.

Cheung GS, Dimmer A, Mellor R, Gale M. A clinical evaluation of conventional bridgework. J Oral Rehabil 1990; 17: 131-36.

Cheung GS, Lai SC, Ng RP. Fate of vital pulps beneath a metal-ceramic crown or a bridge retainer. Int Endod J 2005; 38: 521-30.

Christensen CJ. Tooth preparation and pulp degeneration. J Am Dent Assoc 1996; 128: 353-354.

Conny DJ, Brown MH. Simplified technique for the removal of fixed partial denture. J Prosthet Dent 1981; 46: 505-508.

Cowell TA, Moore J. New technique for sectional model production for inlay and bridgework. J Am Dent Assoc 1965; 71: 1387-90.

Craddock HL, Youngson CC. Incidence and extent of over eruption of unopposed posterior teeth. Br Dent J 2004; 6: 341-348.

Cranin A, Degrade J, Kaufman M, Baraoidan M. Evaluation of the Periotest as a diagnostic tool for dental implants. J Oral Implant 1998; 24: 139-146.

Creugers NH. Resin-bonded bridges. A status report for the American Journal of Dentistry. Am J Dent 1991; 4: 251-55.

Creugers NH, De Kanter RJ, Verzijden CW, Van't Hof MA. Risk factors and multiple failures in posterior resin-bonded bridges in a 5-year multi-practice clinical trial. J Dent 1998; 26: 397-402.

Creugers NH, De Kanter RJ, van't Hof MA. Long-term survival data from a clinical trial on resin-bonded bridges. J Dent 1997; 25: 239-42.

Creugers NH, Snoek PA, Van't Hof MA, Kayser AF. Clinical performance of resin-bonded bridges;a 5-year prospective study.I. Design of the study and influence of expermintal variables. J Oral Rehabil 1989; 16: 427-37.

Creugers NH, Kayser AF, van't Hof MA. A meta-analysis of durability data on conventional fixed bridges. Community Dent Oral Epidemiol 1994; 22: 448-52.

Creugers NH, Mentink AGB, Kayser AF. An analysis of durability data on post and core restoration. J Dent 1993; 21: 281-90.

Creugers NH, van't Hof MA, Vrijhoef MM. A clinical comparison of three types of resin-retained cast metal prostheses. J Prosthet Dent 1986; 56: 297-300.

Crispin BJ. A longitudinal clinical study of bonded fixed partial dentures: the first 5 years. J Prosthet Dent 1991; 66: 336-42.

Curtis DA, Plesh O, Sharma A, Finzen F. Complications associated with fixed partial dentures with a loose retainer. J Prosthet Dent 2006; 96; 245-51.

Dahl BL. Dentine/pulp reaction to full crown preparation procedures. J Oral Rehabil 1977; 4: 247.

Dahl BL, Orstavik D, Karlsen K. Causes for failures/complications in restorative treatment with large fixed bridges. Nor Tannlaegeforen Tid 1987; 97: 460-64. (English Abstract)

Derhami K, Wolfaardt JF, Faulkner G, Grace M. Assessment of the Periotest device in baseline mobility measurements of ctinofacial implants. Int J Oral Maxillofac Implant 1995; 10: 221-229.

Egger GD, Smith GD, Altmann GD. Systemic review in health care: meta-analysis in context, 2nd edn. Problems and limitation in conducting systematic reviews. London: BMJ; 2001.

Elbrashi MK, Craig RG, Peyton FA. Experimental stress analysis of dental restortations. Part IV. The concept of parallelism of axial walls. J Prosthet Dent 1969; 22: 346-51.

Erhardson S. Pore distribution and fracture localization of flame-soldered joints in dental gold. A metallographic and microfractographic study. Acta Odontol Scand 1983; 41: 293-99.

Ericson S, Hedegard B, Wennstrom A. Roentgenographic study of vital abutment teeth. J Prosthet Dent 1966; 16: 981-87.

Ettala-Ylitalo UM, Markkanen H, Yli-Urpo A. Occlusal interferences analysed in patients treated with fixed prosthesis four years earlier. J Oral Rehabil 1986; 13: 395-99.

Fearon JP, Youngson CC. Crowns and the dentino-pulpal complex. CPD Dentistry 2001; 2: 55-59.

Foster LV. Failed conventional bridge work from general dental practice: clinical aspects and treatment needs of 142 cases. Br Dent J 1990; 168: 199-201.

Fox K, Wood DJ, Youngson CC. A clinical report of 85 fractured metallic post-retained crowns. Int Endod J 2004; 37: 561-573.

Fox K, Wood DJ, Youngson CC. An investigation of the constituent elements and mode of fracture of in vivo fractured metallic posts. J Dent 2007; 35: 43-49.

Friberg B, Sennerby L, Meredith N, Lekholm U. A comparison between cutting torque and resonance frequency measurements of maxillary implants. A 20-month clinical study. Int J Oral Maxillofac Surg 1999; 28: 297-303.

Gardner IA, Greiner M. Receiver operating characteristic curves and likelihood ratios: improvements over traditional methods for the evaluation and application of veterinary clinical pathology tests. Vet Clin Pathol. 2006; 35: 8-17.

Garver DG, Wisser RC. A safe crown-removal technique. J Prosthet Dent 1978; 39: 56-58.

Gesi A, Magnolfi S, Goracci C, Ferrari M. Comparison of two techniques for removing fiber posts. J Endod 2003; 29: 580–92.

Glantz PO, Nilner K, Jedresen M, Sundberg H. Quality of fixed prosthodontics after 15 years. Acta Odontol Scand 1993; 51: 247-52.

Glauser R, Ree A, Lundgren A, Gottlow J, Hammerle CH, Scharer P. Immediate occlusal loading of Branemark implants applied in various jawbone regions: a prospective 1 year clinical study. Clin Implant Dent Relat Res 2001; 3: 204-13.

Glauser R, Sennerby L, Meredith N, Lundgren A, Gottlow J, Hammerle CH. Resonance frequency analysis of implants subjected to immediate or early functional occlusal loading, Successful vs. Failing implants. Clin Oral Implant Res 2004; 15: 428-434.

Gluskin AH, Ahmad I, Herrero DB. The aesthetic post and core: unifying radicular form and structure. Pract Proced Aesthet Dent 2002; 14: 313–22.

Gluskin AH, Ruddle CJ, Zinman EJ. Thermal injury through intraradicular heat transfer using ultrasonic devices: precautions and practical preventive strategies. J Am Dent Assoc 2005; 136: 1286-93.

Gomes AP, Kubo CH, Santos RA, Santos DR, Padilha RQ. The influence of ultrasound on the retention of cast posts cemented with different agents. Int Endod J 2001; 34: 93–99.

Goodacre CJ, Bernal G, Rungcharassaeng K, Kan JY. Clinical complications in fixed prosthodontics. J Prosthet Dent 2003; 90: 31-41.

Goodacre CJ, Spolnik KJ. The prosthodontic management of endodontically treated teeth: a literature review. Part III. Tooth preparation considerations. J Prosthodont 1995; 4: 122-28.

Graver DG, Wiser RC. A safe crown removal technique. J Prosthet Dent 1979; 39: 56-58.

Greiner M, Pfeiffer D , Smith RD. Principles and practical application of the receiver operating characteristic analysis for diagnostic tests. Prevent Vet Med 2000; 45: 23-41.

Gratton DR, Jordan RE, Teteruck WR. Resin-bonded bridges: the state of the art. Int Dent 1983; 60; 9-11,13-6, 18-9.

Hammerle CH. Success and failure of fixed bridgework. Periodontol 2000, 1994; 4: 41-51.

Hammerle CH, Ungerer MC, Fantoni, Bragger U, Burgin W, Lang NP. Long-term analysis of biologic and technical aspects of fixed partial dentures with cantilevers. Int J Prosthodont 2000; 13: 409-15.

Hanau RL, Articulation defined, analyzed and formulated. J Am Dent Assoc 1964; 8. 326-333.

Hanley JA, McNeil BJ. The meaning and use of the area under a receiver operating characteristic (ROC) curve. Radiol 1982; 143; 29-36.

Hayashi M, Kobayashi C, Ogata H, Yamaoka M, Ogiso B. A non-contact vibration device for measuring implant stability. Clin Oral Impl Res 2010; 21: 931-936.

Heydecke G, Butz F, Hussein A, Strub JR. Fracture strength after dynamic loading of endodontically treated teeth restored with different post-and core systems. J Prosthet Dent 2002; 87: 438-445.

Helkimo E, Ingervall B. Bite force and functional state of the masticatory system in young men. Swed Dent J 1978; 2: 167-75.

Helkimo E, Carlsson GE, Helkimo M. Bite force and state of dentition. Acta Odondol Scand 1977; 35: 297-303.

Heydecke G, Butz F, Hussein A, Strub JR. Fracture strength after dynamic loading of endodontically treated teeth restored with different post-core systems. J Prosthet Dent 2002; 87: 438-445.

Heyse RJ, Fitzgerald M, Heys DR, Charbeneau GT. An evaluation of a glass ionomer luting agent: pulpal histological response. J Am Dent Assoc 1987; 114: 607-15.

Hildebrond G.Y. Studies in dental prosthetics. Svenk Tandlâkar tidskrift 1937; 30 (suppl. 1).

Hochman N, Mitelman L, Hadani PE, Zalkind M. A clinical and radiographic evaluation of fixed partial dentures (FPDs) prepared by dental school students: a retrospective study. J Oral Rehabil 2003; 30: 165-70.

Howe DF, Denehy GE. Anterior fixed partial dentures utilizing the acid-etch technique and a cast metal framework. J Prosthet Dent 1977; 37: 28-31.

Hussey DL, Linden GJ. The clinical performance of cantilevered resin-bonded bridgework. J Dent 1996; 24: 251-56.

Hurzeler MB, Quinones CR, Schupbach P, Vlassis JM, Strub JR. Influence of the suprastructure on the peri-implant tissues in beagle dogs. Clin Oral Implants Res 1995; 6: 139-148.

Huysmans M, Van Der Varst P, Schafer R, Peters M, Plasschaert A, Soltesz U. Fatigue behaviour of direct post-and core restored premolars. J Dent Res 1992; 71: 1145-50.

Ibsen RL. Fixed prosthetics with a natural crown pontic using an adhesive composite. Case history. J South Calif Dent Assoc 1973; 41: 100-102.

Isidor F, Budtz-Jorgensen E. Periodontal conditions following treatment with distally extending cantilever bridges or removable partial dentures in elderly patients. A 5-year study. J Periodontol 1990; 61: 21-26.

Jackson CR, Skidmore AE, Rice RT. Pulpal evaluation of teeth restored with fixed prostheses. J Prosthet Dent 1992; 67: 323-25.

Jacobsen PH. Failures in conservative dentistry; 4. Crowns. Dent Update 1983; 10: 9-13, 15-6.

Jerge CR, Orlowski RM. Quality assurance and the dental record. Dent Clin North Am 1985; 29: 483-96.

Johansson CB, Albrektsson T. A removal torque and histomorphometric study of commercially pure niobium and titanium implants in rabbit bone. Clin Oral Implants Res 1991; 2: 24-29.

Jorgensen KD. Factors affecting the film thickness of zinc phosphate cements. Acta Odontol Scand 1960; 18; 479-82.

Jorgensen KD. The relationship between retention and convergence angle in cemented veneer crowns. Acta Odontol Scand 1955; 13: 35-40.

Kaneko T. Assessment of the interfacial rigidity of bone implants from vibrational signals. J Mat Sci 1987; 22: 3495-3502.

Kaneko T. Pulsed oscillation technique for assessing the mechanical state of the dental implant-bone interface. Biomaterials 1991; 12: 555-60.

Kaneko T, Nagai Y, Ogino M, Futami T, Ichimura T. Acoustoelectric technique for assessing the mechanical state of the dental-implant bone interface. J Biomed Mat Res 1986; 20: 169-176.

Kantor ME, Pines MS. A comparative study of restorative techniques for pulpless teeth. J Prosthet Dent 1977; 38: 405-12.

Kantorowicz GF. Bridges: an analysis of failures. Dent Practit 1968; 18: 176-78.

Karlsson S. A clinical evaluation of fixed bridges, 10 years following insertion. J Oral Rehabil 1986; 13: 423-32.

Karlsson S. Failures and length of service in fixed prosthodontics after long-term function. A longtitudinal clinical study. Swed Dent J 1989; 13: 185-92.

Kaufman E G, Coelho DH, Colin L. Factors influencing the retention of cemented gold castings. J Prosthet Dent 1961: 11: 487-502.

Kayser AF. Shortened dental and oral function. J Oral Rehabil, 1981; 8: 457-462.

Kayser AF, Van der Hoeven JS. Colorimetric determination of the masticatory performance. J Oral Rehabil 1977; 4: 145-148.

Kim S, Trowbridge H. Pulpal reaction to caries and dental procedures. In: Cohen S, Burns RC, eds. Pathways of the pulp, 7th edn. 1998, St Louis, MO: Mosby, pp.532-51

Kishimoto M, Shillingburg HT, Duncanson MG. Influence of preparation features on retention and resistance. Part II; Three-quarter crowns. J Prosthet Dent 1983; 49: 188-192.

Kleier DJ, Shibilski K, Averbach RE. Radiographic appearance of titanium posts in endodontically treated teeth. J Endod 1999; 25: 128–33.

Kovarik RE, Breeding LC, Caughman WF. Fatigue life of three core materials under simulated chewing condition. J Prosthet Dent 1992; 68: 584-90.

LaBarre EE, Russell D. Update on resin-bonded bridges. Calif Dent Assoc J 1984; 12: 108-11.

LaBarre EE, Ward HE. An alternative resin-bonded restoration. J Prosthet Dent 1984; 52; 247-49.

Lachmann S, Laval JY, Jager B. Resonance frequency analysis and damping capacity assessment. Part 2: peri-implant bone loss follow-up. An *in-vitro* study with the Periotest and Osstell instruments. Clin Oral Implant Res 2006; 17: 80-84.

Landolt A, Lang NP. Results and failures in extension bridges. A clinical and roentgenological follow-up study of free-end bridges. Schweizerische Monatsschrift fur Zahnmedizin 1988; 98: 239-244. (English Abstract)

Langeland K, Langeland LK. Pulp reactions to crown preparation, impression, temporary crown fixation and permanent cementation. J Prosthet Dent 1965; 15: 129-43.

Laurell L, Lundgren D, Falk H, Hugoson A. Long-term prognosis of extensive polyunit cantilevered fixed partial dentures. J Prosthet Dent 1991; 66: 545-52.

Leempoel PJ, Käyser AF, Van Rossum GM, De Haan AF. The survival rate of bridges. A study of 1674 bridges in 40 dutch general practices. J Oral Rehabil 1995; 22: 327-30.

Lekholm U, Sennerby L, Roos J, Becker W. Soft tissue and marginal bone conditions at Osseointegrated implants that have exposed threads: a 5-year retrospective study. Int J Oral Maxillofac Implant 1996; 11; 599-604.

Lekholm U, Zarb GA. Patient selection and preparation. In: Branemark PI, Zarb GA and Albrekesson T. Tissue-integrated prostheses. 1985; pp.199-209. Chicago: Quintessence.

Lewis R, Smith BGN. A clinical study of failed post retained crown. Br Dent J 1988; 163: 95-97.

Lewis RM, Owen MM. A mathematical solution of a problem in full crown construction. Am Dent Assoc 1959; 59: 943-47.

Liebenberg WH. Modification to a safe crown removal technique. A case report. Br Dent J 1994; 176: 71-73.

Langeland K, Langeland LK. Pulp reactions to crown preparation, impression, temporary crown fixation and permanent cemenataion. J Prosthet Dent 1965; 15: 129-43.

Livaditis GJ. Cast metal resin-bonded retainers for posterior teeth. J Am Dent Assoc 1980; 101: 926-29.

Livaditis GJ, Thompson VP. Etched castings: an improved retentive mechanism for resin-bonded retainers. J Prosthet Dent 1982; 47: 52-58.

Livaditis GJ. Etched-metal resin-bonded intracoronal cast restorations. Part I: The attachment mechanism. J Prosthet Dent 1986; 56: 267-74.

Lockard MW. A retrospective study of pulpal response in vital adult teeth prepared for complete coverage restorations at ultrahigh speed using only air coolant. J Prosthet Dent 2002; 88: 473-78.

Lundgren D, Laurell L. Occlusal force pattern chewing and biting in dentitions restored with fixed bridges of cross-arch extension II. Unilateral posterior two-unit cantilevers. J Oral Rehabil 1986; 13: 191-203.

Machtou P. Irrigation in endodontics. Acta Odontolostomatol 1980; 34: 387-94.

Marinello CP, Belser UC. The adhesive bridge alternative maintenance of dental spaces? A review. Schweiz Monatsschr Zahnmed 1985; 95: 194-229. (English Abstract)

Maryniuk GA, Kaplan SH. Longevity of restorations: survey results of dentists' estimates and attitudes. J Am Dent Assoc 1986; 112: 39-45.

Meredith N, Alleyne D, Cawley P. Quantitative determination of the stability of the implant-tissue interface using resonance frequency analysis. Clin Oral Implant Res 1996; 7: 261-67.

Meredith N, Book K, Friberg B, Jemet, Sennerby L. Resonance frequency measurements of implant stability in vivo. A cross-sectional and longitudinal study of resonance frequency measurements on implants in the edentulous and partially dentate maxilla. Clin Oral Implant Res 1997; 8: 226-33.

Meredith N, Friberg B, Sennerby L, Aparicio C. Relationship between contact time measurements and PTV values when using the Periotest to measure implant stability. Int J Prosthodont 1998; 11: 269-75.

Meredith N, Shagaldi F, Alleyne D, Sennerby L, Cawley P. The application of resonance frequency measurements to study the stability of titanium implants during healing in the rabbit tibia. Clin Oral Implant Res 1997; 8: 234-43.

Meredith N. A review of non-destructive test methods and their application to measure the stability and osseointegration of bone anchored endosseous implants. Crit Rev Biomed Eng 1998a; 26: 275-91.

Meredith N. Assessment of implant stability as a prognostic determination. Int J Prosthodont 1998b; 11: 491-501.

Molven O, Halse A, Grug B. Surgical management of endodontic failure: indications and treatment results. Int Dent J 1991; 41: 33-42.

Morrant GA. The systems of the acrylic resin activators and the various clinical technics related to them. Int Dent 1955; 37: 28-42.

Morgan C, Djemal S, Gilmour G. Predictable resin-bonded bridges in general dental practice. Dent Update 2000; 28: 501-6, 508.

Morgano SM, Milot P. Clinical success of cast metal posts and cores. J Prosthet Dent 1993; 70: 11-16.

Morris HE, Ochi S, Crum P, Orenstein I, Plezia R. Bone density: its influence on implant stability after uncovering. J Oral Implantol 2003; 29: 263-269.

Nanci A. Ten Cate's, Oral Histology: development, structure and function. Sixth edition, Mosby 2003.

Nedir R, Bischof M, Szmukler-Moncler S, Brenard J, Samson J. Predicting osseointegration by means of implant primary stability. Clin Oral Implant Res 2004; 15: 520-528.

Nyman S, Ericsson I. The capacity of reduced periodontal tissues to support fixed bridgework. J Clin Periodontol 1982; 9: 409-14.

Nyman S, Lindhe J. A longitudinal study of combined periodontal and prosthetic treatment of patients with advanced periodontal disease. J Periodontol 1979; 50: 163-69.

Olgart L, Bergenholtz G. The dentine/pulp complex: responses to adverse influences. In: Bergenholtz G, Horsted-Binslev P and Reit C. 2003, eds. Textbook of Endontology. Oxford: Blackwell Munksgaard.pp.21-42.

Olin PS, Hill EM, Donahue JL. Clinical evaluation of resin-bonded bridges: a retrospective study. Quintessence Int 1991; 22: 873-77.

Oliva RA. Clinical evaluation of a new crown and fixed partial denture remover. J Prosthet Dent 1980; 44: 267-269.

Oliva RA. Review of the methods for removing cast gold restorations. J Am Dent Assoc 1979; 99: 840-47.

Olive J, Aparicio C. Periotest method as a measure of osseointegrated oral implant stability. Int J Oral Maxillofac Implant 1990; 5: 390-400.

Ostman PO, Hellman M, Sennerby L. Direct implant loading in the edentulous maxilla using a bone density-adapted surgical protocol and primary implant stability criteria for inclusion. Clin Implant Dent Relat Res. 2005; 7 (Suppl 1): S60-69.

Ostman PO, Hellman M, Sennerby L. Immediate occlusal loading of implants in the partially edentate mandible: a prospective 1-year radiographic and 4-year clinical study. Int J Oral Maxillofac Implant 2008; 23: 315-22.

O'Sullivan D, Sennerby L, Meredith N. Measurements comparing the initial stability of five designs of dental implants: a human cadaver study. Clin Implant Dent Relat Res 2000; 2: 85-92.

O'Sullivan D, Sennerby L, Meredith N. Measurements comparing the initial stability of five designs of dental implants: a human cadaver study. Clin Implant Dent Relat Res 2000; 3: 85-92.

O'Sullivan D, Sennerby L, Meredith N. Influence of implant taper on the primary and secondary stability of Osseointegrated titanium implants. Clin Implant Dent Relat Res 2004; 15: 474-480.

Palmqvist S, Soderfeldt B. Multivariate analyses of factors influencing the longevity of fixed partial dentures, retainers, and abutments. J Prosthet Dent 1994; 71: 245-50.

Peciuliene V, Rimkuviene J, Maneliene R, Pletkus R. Factors influencing the removal of posts. Stomatologija. 2005; 7: 21-3. (English Abstract)

Pilo R, Tamse A. Residual dentin thickness in mandibular premolars prepared with Gates Glidden and Prapost drills. J Prosthet Dent 2000; 83: 617-23.

Pjetursson BE, Bragger U, Lang NP, Zwahlen M. Comparison of survival and complication rates of tooth-supported fixed dental prostheses (FDPs) and implant supported FDPs and single crowns. Clin Oral Implant Res 2007; 18 (Suppl 3): 97-113.

Pjetursson BE, Lang NP. Prosthetic treatment planning on the basis of scientific evidence. J Oral Rehabil 2008; 35 (Suppl): 72-79.

Pjetursson BE, Tan K, Lang NP, Bragger U, Egger M, Zwahlen M. A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years-I. Implant supported FPDs. Clin Oral Implant Res 2004a; 15: 625-642.

Pjetursson BE, Tan K, Lang NP, Bragger U, Egger M, Zwahlen M. A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years-IV. Cantilever or extention FPDs. Clin Oral Implant Res 2004b; 15: 667-676.

Pope MS. The Statistical Evaluation of Medical Tests for Classification and Prediction. New York, NY: Oxford University Press; 2003.

Potts RG, Shillingburg HT, Duncanson MG. Retention and resistance of preparations for cast restorations. J Prosthet Dent 2004; 92: 207-212.

Ramakrishna R, Sanjna N. Clinical assessment of primary stability of endosseous implants placed in the incisor region, using resonance frequency analysis methodology: An *in vivo* study. Ind J Dent Res, 2007; 18: 168-172.

Ramfjord SP. Periodontal aspects of restorative dentistry. J Oral Rehabil, 1974; 1: 107-26.

Ramfjord SP, Ash MM. Occlusion. Philadelphia, WB Saunders Co., 1971, Chapters 4 and 10.

Rammelsberg P, Pospiech P, Gernet W. Clinical factors affecting adhesive fixed partial dentures: a 6-year study. J Prosthet Dent 1993; 70: 300-307.

Randow K, Glantz PO, Zoger Bo. Technical failures and some related clinical implications in extensive fixed prosthetics. Acta Odontol Scand 1986; 44: 241-55.

Reisbick MH, Matyas J. The accuracy of highly filled elastomers impression materials. J Prosthet Dent 1975; 33: 67-72.

Reisbick MH, Shillingburg HT. Effect of preparation geometry on retention and resistance of cast gold restorations. Calif Dent Assoc J 1975; 3: 51-59.

Reuter JE, Borse MO. Failures in full crown retained dental bridges. Br Dent J 1984; 157: 61-63.

Roberts DH. The failure of retainers in bridge prostheses. An analysis of 2,000 retainers. Br Dent J 1970; 128: 117-24.

Roberts DH. Fixed Bridge Prostheses. 1980 Bristol, John Wright and Sons.

Rochette AL. Attachment of a splint to enamel of lower anterior teeth. J Prosthet Dent 1973; 30: 418-23.

Rosenstiel E. The retention of inlays and crowns as a function of geometrical form. Br Dent J 1957; 2: 103: 388-394.

Ruddle CJ. Nonsurgical retreatment. J Endod 2004; 30: 827–45

Salvi GE, Lang NP. Diagnosis parameters for monitoring peri-implant conditions. Int J Oral Maxillofac Implant 2004; 19 (Suppl): 116-127.

Sapone J, Lorencki SF. An endodontic-prosthodontic approach to internal tooth re-enforcement. J Prosthet Dent 1981; 45: 164-74.

Saunders WP. The influence of chemically active composite resins upon the tensile retentive impact strength of resin bonded bridges. Rest Dent 1986; 2: 86, 88-90.

Saunders WP, Saunders EM. Prevalance of periradicular periodontitis associated with crowned teeth in an adult scottish subpopulation. Br Dent J 1998; 185: 137-140.

Schulte W, Lukas D. The Periotest method. Int Dent J 1992; 42: 433-440.

Schulte W, d'Hoedt B, Lukas D, Muhlbradt L, Scholz F, Bretschi J, Frey D, Gudat H, Konig M, Markl M. Periotest-a new measurement process for periodontal function. Zahnarztl Mitt. 1983; 73: 1229-40. (English Abstract)

Schuyler CH. Factors of occlusion applicable to restorative dentistry. J Prosthet Dent 1953; 3: 772-782.

Schwartz NL, Whitsett LD, Berry TG, Stewart JL. Unserviceable crowns and fixed partial dentures: Life-span and causes for loss of serviceability. J Am Dent Assoc 1970: 81: 1395-401.

Sedgley CM, Messer HH. Are endodontically treated teeth more brittle? J Endodont 1992; 18: 332-35.

Selby A. Fixed prosthodontic failure. A review and discussion of important aspects. Austr Dent J 1994; 39: 150-56.

Seltzer S, Bender IB. Early human pulp reactions to full crown preparations. J Am Dent Assoc 1959; 59: 915-23.

Sennerby L, Ericson LE, Thomsen P, Lekholm U, Astrand P. Structure of the bone-titanium interface in retrieved clinical oral implants. Clin Oral Implant Res 1991; 2: 103-11.

Sennerby L, Gottlow J. Clinical outcomes of immediate/early loading of dental implants. A literature review of recent controlled prospective clinical studies. Austr Dent J 2008; 53 (Suppl): S82-S86.

Sennerby L, Meredith N. Resonance frequency analysis: measuring implant stability and osseointegration. Compend Contin Educ Dent 1998; 19: 493-98.

Sennerby L, Meredith N. Implant stability measurements using resonance frequency analysis: biological and biomechanical aspects and clinical implications. Periodontol 2000 2008; 47: 51-66.

Sennerby L, Thomsen P, Ericson LE. A morphometric and biomechanic comparison of titanium implants inserted in rabbit cortical and cancellous bone. Int J Oral Maxillofac Implant 1992; 7: 62-71.

Sennerby L. Dental implants: matters of course and controversies. Periodontol 2000 2008; 47: 9-14.

Serway RA. Physics for Scientists and Engineers 4th Edition Volume 2. Saunders College Publishing 1996; p.949.

Shillingburg HT, Hobo S, Whitsett LD, Jacobi R, Brackett SE. Fundamentals of fixed prosthodontics. 3rd ed: Quintessence books, Chicago, 1997.

Shillingburg HT, Kessler JC, Wilson EL. Root dimensions and dowel size. Calif Dent Assoc J 1982; 10: 43-49.

Silness J. Distribution of artificial crowns and fixed partial dentures. J Prosthet Dent 1970; 23: 641-647.

Simon JF, Gartrell RG, Grogono A. Improved retention of acid-etched fixed partial dentures: a longitudinal study. J Prosthet Dent 1992; 68: 611-15.

Simonsen RJ. Preventive resin restorations (II). Quintessence Int Dent Digest 1978; 9: 95-102.

Sjöström M, Lundgren S, Nilson H, Sennerby L. Monitoring of implant stability in grafted bone using resonance frequency analysis. A clinical study from implant placement to 6 months of loading. Int J Oral Maxillofac Surg 2005; 34: 45-51.

Smith BGN, Howe LC. Planning and Making Crowns and Bridges. 4th edition, 2007. Informa Health Care 2007.

Smyd ES. Advanced thought in indirect inlay and fixed bridge fabrication, Part I. J Am Dent Assoc 1944; 31: 759-768.

Sokol DJ. Effective use of current core and post concepts. J Prosthet Dent 1984; 52: 231-34.

Sorensen JA, Martinoff JT. Endodontically treated teeth as abutments. J Prosthet Dent 1985; 53: 631-36.

Stamos DE, Gutmann JL. Survey of endodontic retreatment methods used to remove intraradicular posts. J Endodont 1993; 19: 366-69.

Standlee JP, Caputo AA. Effect of surface design on retention of dowels cemented with a resin. J Prosthet Dent 1993; 70: 403-05.

Stanley HR, Swerdlow H. Reaction of the human pulp to cavity preparation: results produced by eight different operative grinding technics. J Am Dent Assoc 1959; 58: 49-59.

Glantz S. Primer of Biostatistics, Fourth Edition. The McGraw-Hill Companies, Inc. 1997.

Stern N, Hirshfeld Z. Principles of preparing endodontically treated teeth for dowel and core restorations. J Prosthet Dent 1973; 30: 162-65.

Sunden S, Grondahl K, Grondahl HG. Accuracy and precision in the radiographic diagnosis of clinical instability in Branemark dental implants. Clin Oral Implant Res 1995; 6: 220-26.

Swartz B, Svenson B, Palmqvist S. Long-term changes in marginal and periapical periodontal conditions in patients with fixed prostheses: a radiographic study. J Oral Rehabil 1996; 23: 101-107.

Swets JA. Measuring the accuracy of diagnostic systems. Science 1988; 240: 1285-1293.

Taleghani M, Morgan RW. Reconstructive materials for endodontically treated teeth. J Prosthet Dent 1987; 57: 446-49.

Tan K, Pjetursson BE, Lang NP, Chan ES. A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years. Clin Oral Implant Res 2004; 15: 654-66.

Teerlinck J, Quirynen M, Darius P. Periotest: An objective clinical diagnosis of bone apposition toward implants. Int J Oral Maxillofac Implant 1991; 6: 55-61.

Torbjorner A, Karlsson S, Odman PA. Survival rate and failure characteristics for two post designs. J Prosthet Dent 1995; 73: 439-44.

Turner CH. Post-retained crown failure: a survey. Dent Update 1982; 9: 221-6,228-29.

Tylman SD. Crowns and fixed partial dentures. J Am Dent Assoc 1950; 40: 675-76.

Valderhaug J, Karlsson K. Frequency and location of artificial crowns and fixed partial dentures constructed at a dental school. J Oral Rehabil 1976; 3: 75-81.

Valderhaug J, Jokstad A, Ambjornsen E, Norhiem PW. Assessment of the periapical and clinical status of crowned teeth over 25 years. J Dent 1997; 25: 97-105.

Valderhaug J. A 15-year clinical evaluation of fixed prosthodontics. Acta Odontol Scand 1991; 49: 35-40.

Van Steenberghe D, Tricio J, Naert I, Nys M. Damping characteristics of bone to implant surfaces. A clinical study with the Periotest device. Clin Oral Implant Res 1995; 6: 31-39.

Veltri M, Balleri P, Ferrari M. Influence of transducer orientation on Osstell stability measurements of osseointegrated implants. Clin Implant Dent Relat Res 2007; 9: 60-64.

Verrett RG, Kaiser DA. Fracture of a fixed partial denture abutment: a clinical report. J Prosthet Dent 2005; 93: 21-23.

Verrett RG, Mansueto MA. Removal of a metal-ceramic fixed partial denture with a loose retainer. J Prosthodont 2003; 12:13-16.

Walker L, Morris HF, Ochi S. Periotest values of dental implants in the first years after second stage surgery: DICRG interim report no.8. Dental Implant Clinical Research Group. Implant Dent 1997; 6: 207-212.

Walls AW, Nohl FS, Wassell RW. Crowns and other extra-coronal restorations: resin-bonded metal restorations. Br Dent J 2002; 193: 135-8, 141-42.

Walton JN, Gardner FM, Agar JR. A survey of crown and fixed partial dentures:length of service and reasons for replacement. J Prosthet Dent 1986: 56: 416-21.

Walton TR. A 10 year longtitudinal study of fixed prosthodontics: Clinical characteristics and outcome of single-unit metal-ceramic crowns. Int J Prosthodont 1999; 12: 519-26.

Wegner PK, Freitag S, Kern M. Survival rate of endodontically treated teeth with posts after prosthetic restoration. J Endodont 2006; 32: 928-31.

Weine FS, Wax AH, Wenckus CS. Retrospective study of tapered, smooth post systems in place for 10 years or more. J Endodont 1991; 17: 293-97.

Willimas VD, Bjorndal AM. The Masserann technique for the removal of fractured posts in endodontically treated teeth. J Prosthet Dent 1983; 49: 46-48.

Wiltshire WA. A classification of resin-bonded bridges based on the evolutionary changes of the different technique type. Quintessence Dent Technol 1987; 11: 253-58.

Zalkind M, Ever-Hadani P, Hochman N. Resin-bonded fixed partial denture retention: a retrospective 13-year follow-up. J Oral Rehabil 2003; 30: 971-77.

Zweig MH, Campbell G. Receiver operating characteristic (ROC) plots; A fundamental evaluation tool in clinical medicine. Clinical Chem 1993, 39: 561-577.